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USER'S MANUAL FOR THREE DIMENSIONAL BOUNDARY LAYER (BL3-D) CODE

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by

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Prepared for:

National Aeronautics and Space Administration
Lewis Research Center

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| 16. Abstract An assessment has been made of the applicability of a three dimensional boundary layer analysis to the calculation of heat transfer, total pressure losses, and streamline flow patterns on the surfaces of both stationary and rotating turbine passages. In support of this effort, an analysis has been developed to calculate a general nonorthogonal surface coordinate system for arbitrary three dimensional surfaces and also to calculate the boundary layer edge conditions for compressible flow using the surface Euler equations and experimental data to calibrate the method, calculations are presented for the pressure endwall, and suction surfaces of a stationary cascade and for the pressure surface of a rotating turbine blade. The results strongly indicate that the three dimensional boundary layer analysis can give good predictions of the flow field, loss, and heat transfer on the pressure, suction, and endwall surface of a gas turbine passage. | | | | | |
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User's Manual for Three Dimensional
Boundary Layer (BL3-D) Code

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1.0 SUMMARY

This User's Manual contains a complete description of the computer codes developed and utilized under NASA contract NAS3-23716 "Assessment of a Three Dimensional Boundary Layer Code to Predict Heat Transfer and Flow Losses in a Turbine". The SETUP code calculates a general nonorthogonal surface coordinate system and the boundary layer edge conditions from a known static surface pressure distribution. The BL3D code utilizes this coordinate system and the edge conditions for the calculation of the three dimensional boundary layer on an arbitrary surface such as a turbine blade or end wall. A companion report to this User's Manual which is entitled "Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine" documents the technical approach used in the SETUP and BL3D codes and presents results which have been obtained in the application of the three dimensional boundary layer theory to the flow in a turbine passage with blade rotation. Although the primary thrust of this work has been for gas turbine application, the compressible three dimensional boundary layer analysis is very general and can be used for a wide range of applications in internal and external aerodynamics.

The User's Manual is essentially divided into two parts. In the first part, Sections 3.0, 4.0, and 5.0, a description of the input, output, and general operation of both codes is presented. In the second part, Sections 6.0 and 7.0, a detailed description of the computer codes including a listing and description of all FORTRAN variables in COMMON blocks and a detailed description of the subroutines are given. These latter sections of the User's Manual are presented for the user who wishes to obtain a detailed understanding of the codes.

2.0 INTRODUCTION

This User's Manual describes the computer codes known collectively as the Three Dimensional Boundary Layer (BL3D) code which was developed under NASA Contract NAS3-23716. A description of the analysis used in the SETUP code is given by Anderson (Ref. 1). A comprehensive outline of the analysis used in the BL3D code is also given by Anderson (Ref. 1). The three dimensional boundary layer analysis used in the BL3D codes was developed by Vatsa (Refs. 2 and 3). Reference 3, in particular, describes in detail the solution algorithm including the finite difference equations and the matrix inversion method. Assessment of these codes for gas turbine applications is also given in Ref. 1 through 3. The SETUP code contains a prepackaged surface spline fitting routine developed by McCartin (Ref. 6) which is not described.

This report is divided into sections for the convenience of the user. Section 3.0 contains an overall description of the computer codes describing how they are linked together functionally and through data files. Sections 4.0 and 5.0 contain a description of the input and output files so that the user can run the codes and interpret the printed output. These sections also contain a sample input data file to assist the user in setting up new cases. Although these codes are very robust, they sometimes fail. If the cause of the failure is known, a DIAGNOSTIC is printed and the calculation is terminated. A description of these failures and DIAGNOSTICS is also given. Sections 3.0 through 5.0 contain all the information required by the user who wishes to run these codes but does not require a detailed understanding of the codes.

Sections 6.0 and 7.0 contain a more detailed description of these computer codes for the user who wishes to modify these codes. These sections are divided into three subsections. The first subsection describes the MAIN program including a global tree structure chart which provides the user with an overview of the code. This section includes all calling and called subroutines. The second subsection contains a list of all FORTRAN symbols which are contained in COMMON blocks. These FORTRAN symbols may be identified with the corresponding algebraic symbols which are the same as those used in Ref. 1. The third subsection contains a detailed description of each subroutine. These subroutine descriptions are arranged according to the same format. First, the object of the subroutine is described. Second, any input options used in the subroutine are described so that the user can understand any branching that takes place. Third, a list of local FORTRAN symbols is given. Finally a description of the analysis used in the subroutine is given. If the analysis is described in Ref. 1, it is referenced by subsection. If the analysis is not described in Ref. 1, it is described in these subroutine descriptions. In cases where well known analyses, such as interpolation formulas, are used the source reference is given.

3.0 GENERAL DESCRIPTION OF BL3D CODE

The Three dimensional boundary layer (BL3D) code requires three separate analyses: 1) an analysis to construct a general nonorthogonal coordinate system for a twisted turbine blade, 2) an analysis referred to as a surface Euler analysis to calculate the boundary layer edge conditions from a known wall static pressure distribution, and 3) an analysis to calculate the three dimensional boundary layer growth on the turbine blade surface. These analyses are contained in two separate computer codes. The SETUP code contains the coordinate analysis and the boundary layer code analysis. The BL3D code contains the boundary layer analysis. A detailed description of the coordinate analysis and boundary layer edge analysis contained in the SETUP code is given by Anderson (Ref. 1). A general outline of the boundary layer analysis contained in the BL3D code is given by Anderson (Ref. 1). A detailed description of the boundary layer analysis including the finite difference equations and the matrix inversion analysis is given by Vatsa (Refs. 2 and 3).

A flow chart describing the operation of these computer codes is shown on Fig. 1. The geometry analysis calculates a surface coordinate system which is required by both the surface Euler analysis and the three dimensional boundary layer analysis. The surface Euler analysis calculates the boundary layer edge conditions. This data is then input into the 3D boundary layer analysis. A brief description of these codes is given below.

Geometry Analysis

Since the boundary layers lie on the blade surface, a convenient coordinate system is a surface coordinate system (X_1, X_2, X_3) which has the properties that two coordinates (X_1, X_2) lie on the blade surface and the third coordinate (X_3) is normal to the blade surface. X_1 is generally taken to be in the streamwise direction and X_2 is generally in the crossflow direction. This coordinate system, in general, must be a non-orthogonal coordinate system, therefore X_1 is not necessarily orthogonal to X_2 . Furthermore we note that a given twisted turbine blade is not a developable surface (i.e., it can not be flattened to a plane surface without distortion). Thus if we describe the turbine blade in Cartesian coordinates (Y_1, Y_2, Y_3) , where Y_1 is generally in the streamwise direction, Y_2 in the crossflow direction, and Y_3 orthogonal to (Y_1, Y_2) , then a mathematical transformation must be found for the relation between the computational coordinates (X_1, X_2, X_3) and the physical coordinates (Y_1, Y_2, Y_3) . In general, the equation of the physical surface can be expressed as $Y_3 = Y_3(Y_1, Y_2)$. Thus if a unique relation can be found $Y_1 = Y_1(X_1, X_2)$ and $Y_2 = Y_2(X_1, X_2)$, then the third coordinate is known $Y_3 = Y_3(X_1, X_2)$. This unique relation is provided by the transfinite mapping of Gordon and Thiel (Ref. 4). Once the transformation from the computational coordinates (X_1, X_2, X_3) to the physical (Cartesian) coordinates is known, the covariant matrix tensor, metric scale coefficients, and the direction cosines from the computational coordinates to the Cartesian coordinates can be determined using the relations given in Ref. 5. In addition it is noted that since the turbine blade surface is only known as numerical data, the surface spline analysis of McCartin (Ref. 6) and Spath (Ref. 7) is used to

interpolate points on the surface and calculate first and second derivatives of the surface. Details of this geometric analysis are given by Anderson (Ref. 1).

Surface Euler Analysis

The three dimensional boundary layer equations require the boundary layer edge conditions, which include the two free stream velocity components, their derivatives, and the free stream temperature, as boundary conditions over the whole computational domain. These may be obtained directly from experimental data, however, in practice it is very expensive to survey an entire three dimensional flow field. These conditions may also be obtained from a solution of the Euler equations. However, since the generation of the passage vortex is viscous in nature, the Euler solutions may not provide good edge conditions for the crossflow without special treatment. A third method is to obtain the edge conditions from the experimental pressure distribution by integrating the surface Euler equations. These surface Euler equations are obtained from the boundary layer equations in the limit as the normal coordinate approaches the edge of the boundary layer so that normal derivatives of all variables go to zero. Since the pressure distribution is known, only two momentum equations and an energy equation are required for a complete solution of all the dependent variables. These surface Euler equations are hyperbolic in character and may be solved using the same computational (X1,X2) grid, finite difference module, and inflow edge conditions as the three-dimensional boundary layer analysis. A detailed presentation of this analysis are given by Anderson (Ref. 1).

3-D Boundary Layer Analysis

The three dimensional boundary layer analysis used in this computer code is that developed by Vatsa (Refs. 2 and 3). This analysis solves the finite difference form of the compressible three-dimensional boundary layer equations (including the energy equation) in a non-orthogonal surface coordinate system which includes Coriolis forces produced by coordinate rotation. These equations are solved in Levy-Lees variables using an efficient, implicit, fully coupled finite difference procedure. These boundary layer equations are hyperbolic in character and require, besides the edge boundary conditions, the inflow conditions along the computational boundaries where flow enters the domain. These inflow conditions are estimated by solving the 3-DBL equations along the inflow boundary using an assumption of either local similarity or plane of symmetry which reduces the equations to two dimensional differential equations with edge conditions provided by the boundary layer edge analysis.

Operation of Computer Codes

The description of the input and output of the SETUP code is given in Section 4.0 and a description of the input and output for the BL3D code is given in Section 5.0. Sample inputs for both codes are given in the respective sections. Since the BL3D code requires the surface coordinate data and the boundary layer edge conditions, the SETUP code must be run first. The linking of these two codes through data files is shown in Fig. 2. Note on Fig. 2 that output Units 8, 9, and 10 for the SETUP code correspond to the input Units 10, 11, and 12 respectively for the BL3D code. Output Units 13, 15, and 16 are

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special output files for CALCOMP or TEKTRONIX plot packages. Since plotting codes are machine dependent, they are not available on the NASA Lewis version of these codes. Unit 20 for the BL3D code serves as both an input and output file.

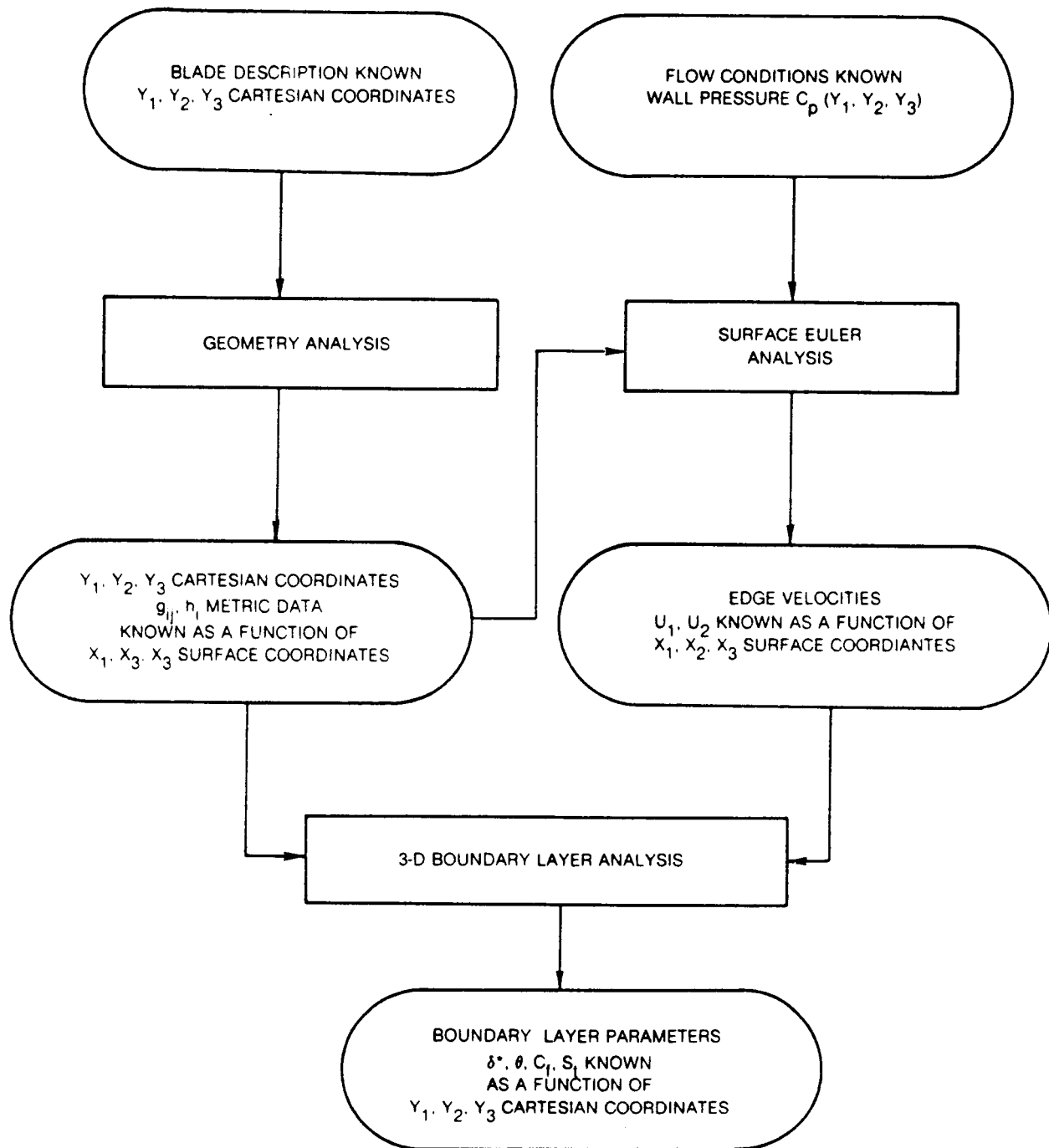


Fig. 1 Flow Chart of Geometry, Surface Euler and 3-D Boundary Layer Analysis

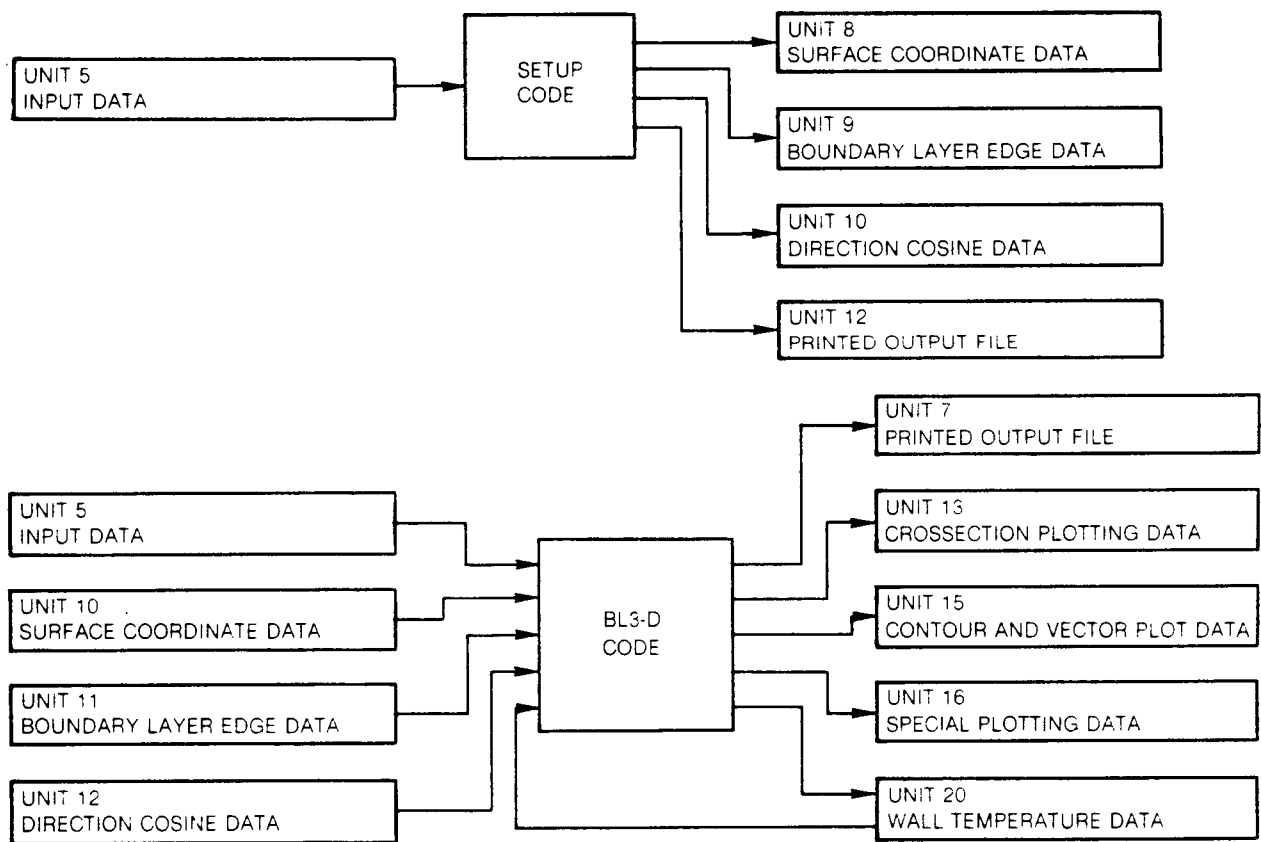


Fig. 2 Data File Links Between Setup and BL3 D Codes

4.0 OPERATION OF SETUP CODE

4.1 Input Format

The input format is described on the pages which follow. The type and amount of data read by the code is controlled by the input options IOPT1 through IOPT12 and the user should be very careful to be sure that the input data agrees with the input options. In general the input cards are loaded as follows:

Card(s) 0 Title Card

Card(s) 1 Computational Grid Data

Card(s) 2 Computational Boundary Data

Card(s) 3 Coordinate Surface Data

Card(s) 4 Pressure Distribution Data

Card(s) 5 Inflow Conditions Data

Card 6 Print Options

Card(s) 7 Reference Flow Variables

Card(s) 8 Rotor Parameters (load only if IOPT8 = 1)

Card(s) 9 Upstream Flow Conditions (load only if IOPT11 = 1)

In the loading of the input cards, the variable name, column numbers, and description are given. Integer numbers are right adjusted and real numbers may have any number of significant digits.

Card(s) 0 Title Card (load 72 alphanumeric characters)Card(s) 1 Computational Grid DataCard 1a Options (8I10)

IOPT4 1-10 Mesh distribution option
 IOPT4 = 0 Calc. uniform grid
 1 Calc. stretched grid
 2 Read grid points

LPLAST 11-20 No. X1 grid points

KPLAST 21-30 No. X2 grid points

Card 1b Stretching Parameter (F10.0) If IOPT4 = 1

A 1-10 Stretching parameter

Card(s) 1b Input grid Points (8F10.0) If IOPT4 = 2

(X1(LP),LP=1,LPLAST) X1 grid points
 Load LPLAST numbers (8 numbers/card)

(X2(KP),KP=1,KPLAST) X2 grid points
 Load KPLAST numbers (8 numbers/card)

Card(s) 2 Computational Boundary DataCard 2a Options (8I10)

IOPT2 1-10 Grid boundary option
 IOPT2 = 0 Cartesian Grid on a plane
 = 1 Skewed grid on a plane
 = 2 1D mapping Y2=Y2(X1,X2)
 = 3 1D mapping Y1=Y1(X1,X2)
 = 4 2D mapping

LPLAST 11-20 No. X1 input boundary points

KPLAST 21-30 No. X2 input boundary points

Card 2b Boundary Corners (5F10.0) If IOPT2 = 0

Y1L 1-10 Lower Y1 boundary

Y1U 11-20 Upper Y1 boundary

Y2L 21-30 Lower Y2 boundary

Y2U 31-40 Upper Y2 boundary

SS10 41-50 Initial arc length on X1

Card 2b Boundary Corners (4F10.0) If IOPT2 = 1

Y100 1-10 Y1(0,0)

Y101 11-20 Y1(0,1)

Y111 21-30 Y1(1,1)

Y110 31-40 Y1(1,0)

Card 2c Boundary Corners (4F10.0) If IOPT2 = 1

Y200 1-10 Y2(0,0)

Y201 11-20 Y2(0,1)

Y211 21-30 Y2(1,1)

Y210 31-40 Y2(1,0)

Card 2b Y1 Boundary Points (2F10.0) If IOPT2 = 2

Y1L 1-10 Lower Y1 boundary

Y1U 11-20 Upper Y1 boundary

Card(s) 2c Side 2 and Side 4 (8F10.0) If(IOPT2 = 2)

(Y1X11(LB),LB=1,LBLAST) Y1 boundary points side 2 (X2 = 1)

(Y2X11(LB),LB=1,LBLAST) Y2 boundary points side 2 (X2 = 1)

(Y1X10(LB),LB=1,LBLAST) Y1 boundary points side 4 (X2 = 0)

(Y2X10(LB),LB=1,LBLAST) Y2 boundary points side 4 (X2 = 0)

Load 4*LBLAST numbers (8 numbers/card)

Card 2b Y2 Boundary Points (2F10.0) If (IOPT2 = 3)

Y1L 1-10 Lower Y1 boundary

Y1U 11-20 Upper Y1 boundary

Card(s) 2c Side 1 and Side 3 (8F10.0) If(IOPT2 = 3)

(Y10X2(KB),KB=1,KBLAST) Y1 boundary points side 1 (X1 = 0)

(Y20X2(KB),KB=1,KBLAST) Y2 boundary points side 1 (X1 = 0)

(Y11X2(KB),KB=1,KBLAST) Y1 boundary points side 3 (X1 = 1)

(Y21X2(KB),KB=1,KBLAST) Y2 boundary points side 3 (X1 = 1)

Load 4*KBLAST numbers (8 numbers/card)

Card(s) 2b Four Sides (8F10.0) If IOPT2 = 4

(Y10X2(KB),KB=1,KBLAST) Y1 boundary points side 1 (X1 = 0)

(Y20X2(KB),KB=1,KBLAST) Y2 boundary points side 1 (X1 = 0)

(Y1X11(LB),LB=1,LBLAST) Y1 boundary points side 2 (X2 = 1)

(Y2X11(LB),LB=1,LBLAST) Y2 boundary points side 2 (X2 = 1)

(Y11X2(KB),KB=1,KBLAST) Y1 boundary points side 3 (X1 = 1)

(Y21X2(KB),KB=1,KBLAST) Y2 boundary points side 3 (X1 = 1)

(Y1X1 ϕ (LB),LB=1,LBLAST) Y1 boundary points side 4 (X2 = 0)

(Y2X1 ϕ (LB),LB=1,LBLAST) Y2 boundary points side 4 (X2 = 0)

Load 4*(LBLAST + KPLAST) numbers (8 numbers/card)

Card(s) 3 Coordinate Surface DataCard 3a Options (3I10)

IOPT1 1-10 Surface geometry option
 IOPT1 = 0 plain surface
 = 1 Y3 = Y3(Y1)
 = 2 Y3 = Y3(Y2)
 = 3 Y3 = Y3(Y1,Y2)

LSLAST 11-20 No. input Y1 points

KSLAST 21-30 No. input Y2 points

Card(s) 3b Surface Coordinates (8F10.0) If IOPT1 = 1

(Y1(LS),LS=1,LSLAST) Y1 coordinate

(Y3(LS),LS=1,LSLAST) Y3 coordinate

Load 2*LSLAST numbers (8 numbers/card)

Card(s) 3b Surface Coordinates (8F10.0) If IOPT1 = 2

(Y2(KS),KS=1,KSLAST) Y2 coordinate

(Y3(KS),KS=1,KSLAST) Y3 coordinate

Load 2*KSLAST numbers (8 numbers/card)

Card(s) 3b Surface Coordinates (8F10.0) If IOPT1 = 3

(Y1(LS),LS=1,LSLAST) Y1 coordinate

Load LSLAST numbers (8 numbers/card)

(Y2(KS),KS=1,KSLAST) Y2 coordinate

Load KSLAST numbers (8 numbers/card)

((Y3(LS,KS),LS=1,LSLAST),KS=1,KSLAST) Y3 coordinate

Load LSLAST*KSLAST numbers (8 numbers/card)

CARD(S) 4 Pressure Distribution DataCard 4a Options _ _ _ _ _ (5110)

| | | |
|--------|-------|---------------------------------|
| IOPT3 | 1-10 | Pressure data option |
| | | IOPT3 = 0 No pressure data |
| | | = 1 CP=CP(X1,X2) |
| | | = 2 CP=CP(Y1,Y2) |
| | | = 3 CP=CP(Y1,X2) |
| | | = 4 CP=CP(X1,Y2) |
| LILAST | 11-20 | No. X1 or Y1 input points |
| KILAST | 21-30 | No. X2 or Y2 input points |
| IOPT7 | 31-40 | SMOOTH CP DATA IOPT7 times |
| IOPT8 | 41-50 | Rotor/Stator option |
| | | IOPT8 = 0 Stator |
| | | = 1 Rotor load data hub to tip |
| | | = -1 Rotor load data tip to hub |

Card(s) 4b Coordinate Data _ _ (8F10.0)

(Y1I(LD),LD=1,LILAST) Y1 Coordinate

Load LILAST numbers (8 numbers/card)

(Y2I(KD),KD=1,KILAST) Y2 Coordinate

Load KILAST numbers (8 numbers/card)

((Y3I(LD,KD),LD=1,LILAST),KD=1,KDLAST) CP (Y1,Y2)

Load LILAST*KILAST numbers (8 numbers/card)

Card(s) 5 Inflow Conditions DataCard 5 Options (3I10)

IOPT5 1-10 Inflow option
 IOPT5 = 0 U1E = SQRT(1-CP) : U2E = 0.0
 IOPT5 > 0 integrate b1 edge equations
 = 1 U2(0,X2) = 0.0 : U2(X1,0) = 0.0
 = 2 U2(0,X2) = 0.0 : U2(X1,0) Input
 = 3 U2(0,X2) Input : U2(X1,0) = 0.0
 = 4 U2(0,X2) Input : U2(X1,0) Input

LULAST 11-20 No. X1 input points

KULAST 21-30 No. X2 input points

Card(s) 5b X2=0 inflow boundary (8F10.0) If IOPT5 = 2

(Y11U(LP),LP=1,LULAST) Y1 coordinate

Load LULAST numbers (8 numbers/card)

(U2X1(LP),LP=1,LULAST) U2(Y1)

Load LULAST numbers (8 numbers/card)

Card(s) 5b X1=0 inflow boundary (8F10.0) If IOPT5 = 3

(Y12U(KP),KP=1,KULAST) Y2 coordinate

Load KULAST numbers (8 numbers/card)

(U2X2(KP),KP=1,KULAST) U2(Y2)

Load KULAST numbers (8 numbers/card)

Card(s) 5b X2=0 inflow boundary (8F10.0) If IOPT5 = 4

(Y11U(LP),LP=1,LULAST) Y1 coordinate

Load LULAST numbers (8 numbers/card)

(U2X1(LP),LP=1,LULAST) U2(Y1)

Load LULAST numbers (8 numbers/card)

(Y12U(KP),KP=1,KULAST) Y2 coordinate

Load KULAST numbers (8 numbers/card)

(U2X2(KP),KP=1,KULAST) U2(Y2) 8 numbers/card)

Load KULAST numbers (8 numbers/card)

Card 6 Print Options (5I10)

| | | |
|--------|-------|---|
| IOPT6 | 1-10 | Print every IOPT6th station |
| IOPT9 | 11-20 | Coordinate print option IOPT9 = 0 Output Y1 and Y2 = 1 Output S1 and S2 |
| IOPT10 | 21-30 | Set IOPT10 = 1 |
| IOPT11 | 31-40 | Upstream conditions IOPT11 = 0 Uniform conditions = 1 Nonuniform conditions |
| IOPT12 | 41-50 | Print data on K = IOPT12th line |

Card(s) 7 Reference Flow Variables (6F10.0)

| | | | |
|-------|-------|--------------------|-----------|
| PINFI | 1-10 | Static pressure | (psf) |
| TINFI | 11-20 | Static temperature | (deg. R.) |
| UINFI | 21-30 | Velocity | (ft/sec) |
| BET1I | 31-40 | Not used | |
| XLREF | 41-50 | Length | (ft) |
| DHINF | 51-60 | Not used | |

Card(s) 8 Rotor Parameters (Load only if IOPT8 = 1)Card 8a Rotation Vector (4F10.0)

| | | | |
|------|-------|---------------------|----------|
| VBTI | 1-10 | Rotor tip speed | (ft/sec) |
| G01 | 11-20 | Components of omega | |
| G02 | 21-30 | in the Y1 ,Y2, Y3 | |
| G03 | 31-40 | directions | |

Card 8b Rotor Parameters (6F10.0)

| | | | |
|--------|-------|-------------------|--|
| RADHI | 1-10 | Hub radius | |
| RADTI | 11-20 | Tip radius | |
| YRADHI | 21-30 | Hub Y2 coordinate | |
| YRADTI | 31-40 | Tip Y2 coordinate | |
| GAPI | 41-50 | Mid span gap | |
| DELCP | 51-60 | Not used | |

Card(s) 9 Upstream Flow Conditions (load only if IOPT11 = 1)

| | | | |
|---------|-------|----------------------------------|-----------|
| Y2RI(K) | 1-10 | Spanwise coordinate (Y2) | |
| PTAI(K) | 11-20 | Inlet absolute total pressure | (psf) |
| TTAI(K) | 21-30 | Inlet absolute total temperature | (deg. R.) |
| UZAI(K) | 31-40 | Inlet axial velocity | (ft/sec) |
| BTRI(K) | 41-50 | Inlet flow angle | (deg.) |

Load KILAST cards

4.2 Output Format

The output for the SETUP code echoes the input data and also lists certain additional calculated data which can be used for input to the BL3D code. The output description is given by headings on the following pages.

Unit 12 Output (file name OUTPUT.DAT)

Title Card

72 alphanumeric characters

Input Options

All input options are listed in order with its value and meaning beside it.

Independent Variables

The input calculation grid points $X1(L)$ and $X2(K)$ are listed as input. If $IOPT4 = 0$ or 1 , the calculated grid points are listed.

Computational Boundaries

The input computational boundaries are listed by sides where:

Side 1 $Y1(0.0, X2)$, $Y2(0.0, X2)$

Side 2 $Y1(X1, 1.0)$, $Y2(X1, 1.0)$

Side 3 $Y1(1.0, X2)$, $Y2(1.0, X2)$

Side 4 $Y1(X1, 0.0)$, $Y2(X1, 0.0)$

are parametric pairs of points describing the boundaries. If $IOPT2 < 4$, the boundaries are calculated and then listed.

Coordinate Surface Data

The Cartesian coordinates of the computational surface are listed next. It is assumed that the independent variable Y_1 is only a function of L and the independent variable Y_2 is only a function of K . These arrays are listed first. Next $Y_3(Y_1, Y_2)$ is listed. For $IOPT1 = 0$, the computational surface is a plane surface and Y_3 is not listed. For $IOPT1 = 1$ or 2 , the surface is a two dimensional (developable) surface $Y_3 = Y_3(Y_1)$ or $Y_3 = Y_3(Y_2)$. With these options only Y_1 and Y_3 are listed or Y_2 and Y_3 .

Pressure Distribution Data

The independent variables are listed first. Again it is assumed that Y_1 or X_1 is only a function of L and Y_2 or X_2 is only a function of K depending upon the input option $IOPT3$. The pressure coefficient data is listed next.

Inflow Conditions (If $IOPT5 > 1$)

The independent variables Y_1 or X_1 are listed first and followed by the inflow velocities $U_2(Y_1)$ or $U_2(X_1)$. Then the independent variable Y_2 or X_2 is listed followed by $U_2(Y_2)$ or $U_2(X_2)$.

Flow Parameters

The following input parameters are listed:

| | | | |
|-------|---------------|------------------------------|-------------------------------------|
| PINFI | p_∞ | Reference static pressure | (psf) |
| TINFI | t_∞ | Reference static temperature | (deg. R.) |
| UINFI | u_∞ | Reference velocity | (ft/sec) |
| BET11 | β_{100} | Reference inlet flow angle | $\text{atan}(U_{ZA}/U_{PR})$ (deg.) |

| | | | |
|--------|------------------|-------------------------------|----------|
| XLREF | l | Reference length | (ft) |
| DHINF | | Not used | |
| VBTI | $V_{B_{\infty}}$ | Rotor tip speed | (ft/sec) |
| G01 | } | Direction cosines of rotation | |
| G02 | | vector with respect to the | |
| G03 | | Cartesian coordinates | |
| RADHI | R_H | Hub Radius | |
| RADTI | R_T | Tip Radius | |
| YRADHI | Y_H | Hub Y2 coordinate | |
| YRADTI | Y_T | Tip Y2 coordinate | |
| GAPI | G_{∞} | Reference gap | |
| DELCP | | Not used | |

The following calculated parameters are listed next. These quantities are nondimensionalized in the same manner as the input to the BL3D code and may be used as input to the BL3D code. Note that rotor parameters are only listed if IOPT8 > 0.

| | | | |
|--------|--------------|---|--|
| PINF | P_{∞} | Reference freestream static pressure | |
| TREF | T_{ref} | Reference static temperature | |
| TINF | T_{∞} | Reference freestream static temperature | |
| HINF | H_{∞} | Reference freestream static enthalpy | |
| DHINF | | Not used | |
| XMINF1 | M_{∞} | Reference freestream Mach number | |
| OMEGA | Ω | Magnitude of rotation vector | |

| | | |
|--------|---|---|
| OMEGA1 | } | Cartesian components of rotation vector |
| OMEGA2 | | |
| OMEGA3 | | |

| | | |
|--------|-----------------------|-------------------------------------|
| VBINF | $V_{B\infty}$ | Reference rotor speed |
| UPINF | $U_{\phi\infty}$ | Reference inlet tangential velocity |
| ALP1I | α_{100} | 90. - BET1I |
| HTABSF | $\tilde{H}_{T\infty}$ | Reference absolute total enthalpy |
| PTABSF | $\tilde{P}_{T\infty}$ | Reference absolute total pressure |

Nonuniform Inflow Conditions (If IOPT8 = 1)

The following inflow conditions are input and listed.

| | | |
|---------|---------------|---|
| Y2RI(K) | Y_2 | Y2 coordinate |
| PTAI(K) | \tilde{P}_T | Inlet absolute total pressure (psf) |
| TTAI(K) | \tilde{t}_T | Inlet absolute total temperature (deg. R) |
| UZAI(K) | U_z | Inlet absolute axial velocity (ft/sec) |
| BTRI(K) | β_1 | Inlet relative flow angle $\text{atan}(UZA/UPR)$ (deg.) |

Rotor Inlet Conditions (if IOPT8 = 1)

The following variables are calculated and listed.

| | | |
|---------|-------------------|----------------------------------|
| Y2RI(K) | Y_2 | Y2 coordinate |
| PT/PINF | $P_T/P_{T\infty}$ | Absolute total pressure ratio |
| TT/TINF | $T_T/T_{T\infty}$ | Absolute total temperature ratio |
| P/PINF | P/P_{∞} | Static pressure ratio |
| T/TINF | T/T_{∞} | Static temperature ratio |

| | | |
|-----|-------------------|---|
| VBB | V_B | Rotor velocity |
| BTA | $\tilde{\beta}_1$ | Absolute inlet flow angle $\text{atan}(UZA/UPA)$ (deg.) |
| UIA | \tilde{U}_1 | Absolute inlet velocity |
| UPA | \tilde{U}_ϕ | Absolute inlet tangential velocity |
| UZA | \tilde{U}_z | Absolute inlet axial velocity |
| UIR | U_1 | Relative inlet velocity |
| UPR | U_ϕ | Relative inlet tangential velocity |
| OMS | Ω_s | Relative inlet vorticity |
| U2S | U_{2s} | Estimated inlet spanwise velocity |

Boundary Layer Edge Conditions

The boundary layer coordinates and edge conditions are calculated on a LPLAST*KPLAST grid. Depending on the input option IOPT6, the following quantities are listed at grid points which are multiples of IOPT6.

| | | |
|-----------|----------------------------------|--|
| L , K | | Coordinate point |
| X1P , X2P | X_1, X_2 | Computational coordinates |
| Y1P , Y2P | Y_1, Y_2 | Cartesian coordinates |
| CP | C_p | Pressure coefficients |
| U1E , U2E | U_{1e}, U_{2e} | Boundary layer edge velocity components |
| DU1EDX1 | $\partial U_{1e} / \partial X_1$ | Boundary layer edge derivatives of the velocity components |
| DU1EDX2 | $\partial U_{1e} / \partial X_2$ | |
| DU2EDX1 | $\partial U_{2e} / \partial X_1$ | |
| DU2EDX2 | $\partial U_{2e} / \partial X_2$ | |

| | | |
|--------|------------|---------------------------------------|
| OMEGA3 | Ω_3 | Vorticity component normal to surface |
| P/PINF | P | Static pressure ratio |
| H/HINF | I | Total enthalpy (rothalpy) ratio |

Unit 11 Output (file name CORSCL.DAT)

The output on unit 11 provides a detailed short listing of all L stations for a given K = KPT station. This output is very useful for aligning a computational coordinate with the corresponding Cartesian coordinate and the arc length along the coordinate surface. It also lists the coordinates of a calculated streamline starting at the point (L = 1 , K = KPT). The pair of points (S1P,SLS) form a parametric curve of the streamline on the surface starting at the point (L = 1,K = KPT). The following variables are currently listed on the file.

| | | |
|--------|------------|---------------------------------------|
| L | | Coordinate point |
| X1P | X_1 | Computational coordinate |
| Y1P | Y_1 | Cartesian coordinate |
| S1P | S_1 | Arc length along X_1 coordinate |
| Y3P | Y_3 | Cartesian coordinate of surface |
| CP | C_p | Static pressure coefficient |
| U1E | U_{1e} | Edge velocity components |
| U2E | U_{2e} | |
| OMEGA3 | Ω_3 | Vorticity component normal to surface |
| SLS | S_{2s} | Spanwise arc length of streamline |
| ALPE | α_e | Flow angle at streamline |

4.3 Output Data Files

The output data files are written on units 8, 9, and 10. These data files contain some of the data which is required as input by the BL3D code. A detailed listing of the files are given below.

Unit 8 Metric Data (7E14.7)

| | | |
|--------|----------------------------------|--|
| HH1 | H_1 | Metric scale coefficient for X1 |
| HH2 | H_2 | Metric scale coefficient for X2 |
| DH11 | $\partial H_1 / \partial X_1$ | $D(HH1)/DX1$ |
| DH12 | $\partial H_1 / \partial X_2$ | $D(HH1)/DX2$ |
| DH21 | $\partial H_2 / \partial X_1$ | $D(HH2)/DX1$ |
| DH22 | $\partial H_2 / \partial X_2$ | $D(HH2)/DX2$ |
| GL12 | G_{12} | Covariant metric tensor component |
| DG | $ G $ | Determinant of covariant metric tensor |
| DG121 | $\partial G_{12} / \partial X_1$ | $D(GL12)/DX1$ |
| DG122 | $\partial G_{12} / \partial X_2$ | $D(GL12)/DX2$ |
| RAD | R | Radius |
| DRAD1 | $\partial R / \partial X_1$ | $D(R)/DX1$ |
| OMEGA3 | $\partial R / \partial X_2$ | $D(R)/DX2$ |

Unit 9 Boundary Layer Edge Conditions (7 14.7)

| | | |
|--------|-------------------------------|------------------|
| U1E | U_{1e} | X1 edge velocity |
| U2E | U_{2e} | X2 edge velocity |
| PP | P | Static pressure |
| DU1DX2 | $\partial U_1 / \partial X_2$ | $D(U1E)/DX2$ |

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DU2DX2 $\partial U_2 / \partial X_2$ D(U2E)/DX2

DU1DX1 $\partial U_1 / \partial X_1$ D(U1E)/DX1

DU2DX1 $\partial U_2 / \partial X_1$ D(U2E)/DX1

HR I Rothalpy

Unit 10 Transformation Variables (7E14.7)

Y1 or S1 X1 coordinate or X1 arc length

Y2 or S2 X2 coordinate or X2 arc length

((GAM(I,J),J=1,3),I=1,3) Direction cosines

Note: If IOPT9 = 0 Y1 and Y2 are written

If IOPT9 = 1 S1 and S2 are written

4.4 Diagnostics

A number of checks are made during the course of the calculation. If a minor error occurs, a DIAGNOSTIC message is printed and the calculation is continued. If a serious error occurs, a DIAGNOSTIC message is printed and the calculation stops. A description of the DIAGNOSTIC message is given below. These messages are always of the form

**** DIAGNOSTIC NO. XX ****

where the number XX refers to one of the errors listed below.

1) ****ERROR** X PT DOES NOT CORRESPOND TO GRID LINE** or

****ERROR** Y PT DOES NOT CORRESPOND TO GRID LINE**

This error is detected in Subroutine INTRLD and occurs whenever the computational boundary lies outside the boundaries of the input surface coordinates or outside the boundaries of the input pressure distribution. This is not a fatal error and the calculation continues by extrapolation of the data. However, the input data should be examined to be certain it is correct and the computational boundaries should be inside the input data boundaries.

2) ****ERROR** 1-D INTERPOLATION ROUTINE CALLED**

HOWEVER NEITHER X NOR Y LIE ON A GRIDLINE

This error ordinarily should not occur, however, due to round off error, an IF test may fail and the error message occurs. This is not a fatal error and the calculation continues.

3) CONVERGENCE DID NOT OCCUR

This error is detected in subroutine UITER and occurs whenever convergence of the successive substitution iteration did not occur or if only imaginary solutions exist. This is a fatal error and the calculation stops. Check to see if the input pressure distribution is correct and that the input inflow conditions are correct. One may also smooth the input data using the IOPT7 option.

4.5 Sample Input

A sample input to the SETUP code is given below card by card as described in Section 4.1. To assist the user in setting up a new case comments are inserted between blocks of data in lower case letters. These comments of course should not be on the input cards.

Card(s) 0 Title Card

LSRR76 PRESSURE SURFACE ROTATING RIG (LEADING EDGE START)

Card(s) 1 Computational Grid Data

| | | |
|-----|----|----|
| 1 | 40 | 40 |
| .48 | | |

Card(s) 2 Computational Boundary Data

| | | | |
|--------|---------|---------|---------|
| 0 | 21 | 21 | |
| .01601 | 0.94699 | 0.01893 | 0.92729 |

Card(s) 3 Coordinate Surface Data

| | | | | | | | |
|---------|---------|---------|---------|---------|---------|---------|---------|
| 3 | 50 | 7 | | | | | |
| 0.01000 | 0.02000 | 0.03000 | 0.04000 | 0.05000 | 0.06000 | 0.07000 | 0.08000 |
| 0.09000 | 0.10000 | 0.12500 | 0.15000 | 0.17500 | 0.20000 | 0.22500 | 0.25000 |
| 0.27500 | 0.30000 | 0.32500 | 0.35000 | 0.37500 | 0.40000 | 0.42500 | 0.45000 |
| 0.47500 | 0.50000 | 0.52500 | 0.55000 | 0.57500 | 0.60000 | 0.62500 | 0.65000 |
| 0.67500 | 0.70000 | 0.72500 | 0.75000 | 0.77500 | 0.80000 | 0.82500 | 0.85000 |
| 0.87500 | 0.90000 | 0.91000 | 0.92000 | 0.93000 | 0.94000 | 0.95000 | 0.96000 |
| 0.97000 | 0.98000 | | | | | | |
| 0.01892 | 0.11828 | 0.23656 | 0.47311 | 0.70967 | 0.82795 | 0.92730 | |
| -.42037 | -.40957 | -.40300 | -.39908 | -.39723 | -.39723 | -.39909 | -.40302 |
| -.40933 | -.41594 | -.43076 | -.44336 | -.45392 | -.46258 | -.46945 | -.47461 |
| -.47813 | -.48006 | -.48045 | -.47932 | -.47670 | -.47261 | -.46705 | -.46003 |
| -.45157 | -.44165 | -.43026 | -.41739 | -.40301 | -.38708 | -.36958 | -.35047 |
| -.32973 | -.30730 | -.28313 | -.25717 | -.22931 | -.19947 | -.16755 | -.13341 |
| -.09689 | -.05780 | -.04139 | -.02451 | -.00716 | .01069 | .02542 | .03137 |
| .03310 | .03140 | | | | | | |
| -.43945 | -.42865 | -.42209 | -.41817 | -.41632 | -.41633 | -.41820 | -.42213 |
| -.42841 | -.43489 | -.44939 | -.46164 | -.47185 | -.48015 | -.48667 | -.49147 |
| -.49463 | -.49620 | -.49620 | -.49465 | -.49158 | -.48697 | -.48083 | -.47315 |
| -.46393 | -.45318 | -.44085 | -.42688 | -.41118 | -.39373 | -.37451 | -.35352 |
| -.33075 | -.30621 | -.27988 | -.25175 | -.22177 | -.18991 | -.15611 | -.12028 |
| -.08234 | -.04217 | -.02543 | -.00831 | .00920 | .02713 | .04187 | .04782 |
| .04955 | .04785 | | | | | | |
| -.46218 | -.45138 | -.44483 | -.44091 | -.43906 | -.43907 | -.44094 | -.44487 |

Card(s) 3 Coordinate Surface Data (Cont'd)

| | | | | | | | |
|---------|---------|---------|---------|---------|---------|---------|---------|
| -.45108 | -.45739 | -.47142 | -.48321 | -.49295 | -.50078 | -.50682 | -.51116 |
| -.51384 | -.51490 | -.51438 | -.51227 | -.50858 | -.50328 | -.49636 | -.48778 |
| -.47754 | -.46560 | -.45193 | -.43641 | -.41896 | -.39957 | -.37824 | -.35501 |
| -.32990 | -.30297 | -.27425 | -.24375 | -.21150 | -.17748 | -.14170 | -.10411 |
| -.06470 | -.02342 | -.00636 | .01101 | .02869 | .04671 | .06145 | .06740 |
| .06913 | .06743 | | | | | | |
| -.50768 | -.49688 | -.49031 | -.48639 | -.48453 | -.48453 | -.48639 | -.49032 |
| -.49628 | -.50213 | -.51503 | -.52570 | -.53434 | -.54107 | -.54601 | -.54924 |
| -.55078 | -.55066 | -.54889 | -.54545 | -.54029 | -.53336 | -.52457 | -.51385 |
| -.50108 | -.48617 | -.46906 | -.44971 | -.42815 | -.40445 | -.37870 | -.35101 |
| -.32148 | -.29021 | -.25728 | -.22276 | -.18672 | -.14922 | -.11032 | -.07003 |
| -.02840 | .01453 | .03207 | .04980 | .06773 | .08587 | .10062 | .10657 |
| .10830 | .10659 | | | | | | |
| -.55319 | -.54238 | -.53581 | -.53188 | -.53001 | -.53000 | -.53185 | -.53575 |
| -.54132 | -.54659 | -.55810 | -.56744 | -.57477 | -.58021 | -.58387 | -.58578 |
| -.58597 | -.58445 | -.58120 | -.57616 | -.56926 | -.56039 | -.54941 | -.53611 |
| -.52026 | -.50166 | -.48022 | -.45616 | -.42973 | -.40121 | -.37080 | -.33871 |
| -.30503 | -.26993 | -.23348 | -.19578 | -.15691 | -.11692 | -.07589 | -.03386 |
| .00913 | .05302 | .07083 | .08876 | .10683 | .12502 | .13978 | .14573 |
| .14746 | .14576 | | | | | | |
| -.57592 | -.56511 | -.55854 | -.55461 | -.55275 | -.55274 | -.55459 | -.55850 |
| -.56381 | -.56877 | -.57953 | -.58815 | -.59479 | -.59956 | -.60253 | -.60374 |
| -.60322 | -.60096 | -.59691 | -.59103 | -.58320 | -.57331 | -.56115 | -.54648 |
| -.52898 | -.50839 | -.48462 | -.45801 | -.42901 | -.39798 | -.36520 | -.33090 |
| -.29522 | -.25830 | -.22023 | -.18111 | -.14100 | -.09997 | -.05808 | -.01536 |
| .02813 | .07237 | .09027 | .10827 | .12639 | .14460 | .15936 | .16532 |
| .16705 | .16534 | | | | | | |
| -.59501 | -.58420 | -.57764 | -.57371 | -.57185 | -.57185 | -.57371 | -.57763 |
| -.58270 | -.58739 | -.59752 | -.60554 | -.61160 | -.61579 | -.61818 | -.61881 |
| -.61768 | -.61479 | -.61008 | -.60348 | -.59487 | -.58411 | -.57097 | -.55514 |
| -.53625 | -.51396 | -.48822 | -.45947 | -.42829 | -.39515 | -.36036 | -.32422 |
| -.28685 | -.24842 | -.20899 | -.16869 | -.12756 | -.08566 | -.04306 | .00021 |
| .04412 | .08863 | .10660 | .12466 | .14282 | .16105 | .17581 | .18176 |
| .18350 | .18179 | | | | | | |

Card(s) 4 Pressure Distribution Data

| 2 | 10 | 7 | 4 | 1 | | | |
|-----------|----------|----------|----------|----------|----------|----------|---------|
| 0.01600 | 0.05600 | 0.09100 | 0.23800 | 0.39300 | 0.53600 | 0.66300 | 0.77100 |
| 0.86200 | 0.94700 | | | | | | |
| 0.01892 | 0.11828 | 0.23656 | 0.47311 | 0.70967 | 0.82795 | 0.92730 | |
| 0.34170 | 0.30740 | 0.25390 | 0.08700 | 0.18180 | -0.08640 | -0.80640 | |
| 0.10400 | 0.15350 | 0.33820 | 0.48250 | 0.57320 | 0.55950 | 0.55950 | |
| 0.10250 | 0.12500 | 0.11780 | 0.34470 | 0.46380 | 0.51730 | 0.51730 | |
| 0.14290 | 0.22310 | 0.03990 | 0.44920 | 0.55130 | 0.56350 | 0.56350 | |
| 0.15000 | 0.22800 | 0.31720 | 0.45170 | 0.54970 | 0.56430 | 0.56430 | |
| 0.02200 | 0.10320 | 0.21260 | 0.33820 | 0.41190 | 0.43380 | 0.43380 | |
| - 0.12850 | -0.11320 | -0.11840 | 0.03430 | 0.10320 | 0.07000 | 0.07000 | |
| - 0.56290 | -0.53210 | -0.47050 | -0.43250 | -0.39840 | -0.44950 | -0.44950 | |
| - 1.17390 | -1.16500 | -1.13420 | -1.10830 | -1.10750 | -1.16750 | -1.16750 | |
| - 2.78660 | -2.73850 | -2.76600 | -2.62450 | -2.69660 | -2.67800 | -2.67800 | |

Card(s) 5 Inflow Conditions Data

| 4 | 6 | 7 | | | | |
|--------|--------|--------|--------|--------|--------|--------|
| 0.0000 | 0.2819 | 0.4950 | 0.6669 | 0.8149 | 0.9480 | |
| 0.1000 | 0.1000 | 0.1000 | 0.1000 | 0.1000 | 0.1000 | |
| 0.0200 | 0.1182 | 0.2366 | 0.4731 | 0.7097 | 0.8280 | 0.9273 |
| 0.1000 | 0.3500 | 0.4500 | 0.4500 | 0.4500 | 0.3500 | 0.1000 |

Card 6 Print Options

| 4 | 0 | 1 | 1 | 31 |
|---|---|---|---|----|
|---|---|---|---|----|

Card(s) 7 Reference Flow Variables

| | | | | | |
|----------|---------|---------|--------|---------|---------|
| 2074.976 | 516.035 | 107.314 | 44.600 | 0.52840 | 0.00000 |
|----------|---------|---------|--------|---------|---------|

Card(s) 8 Rotor Parameters (load only if IOPT8 = 1)

| | | | | | |
|---------|----------|---------|---------|-------|---------|
| 107.338 | -1.00000 | 0.00000 | 0.00000 | | |
| 3.8039 | 4.7158 | 0.01829 | 0.92733 | 0.956 | 0.50000 |

Card(s) 9 Upstream Flow Conditions (load only if IOPT11 = 1)

| | | | | |
|--------|----------|---------|--------|--------|
| 0.0200 | 2117.000 | 519.000 | 75.351 | 40.000 |
| 0.1182 | 2117.000 | 519.000 | 75.351 | 40.000 |
| 0.2366 | 2117.000 | 519.000 | 75.351 | 39.000 |
| 0.4731 | 2117.000 | 519.000 | 75.351 | 44.600 |
| 0.7097 | 2117.000 | 519.000 | 75.351 | 42.000 |
| 0.8280 | 2117.000 | 519.000 | 75.351 | 47.000 |
| 0.9273 | 2117.000 | 519.000 | 75.351 | 50.000 |

5.0 OPERATION OF BL3D CODE

5.1 Input Format

The card input format is described on the pages which follow. In addition to the card input, the code also reads input data files contained on units 10, 11, 12 which may be set up by the user or may be set up by the SETUP preprocessor code. In the loading of the cards the variable name, column numbers, and description are given. Integer variables are all right adjusted and real variables may have any number of significant figures.

Card 1 Title card (load 72 alphanumeric characters)

Card 2 Option Card (6I2,8X,3F10.0)

| | | |
|--------|-------|---|
| IGBAR | 1-2 | Levy-Lees option (recommended 0) IGBAR = 0 Laminar Levy-Lees variables = 1 Turbulent Levy-Lees variables |
| ITURB | 3-4 | Turbulence option ITURB = 0 Laminar flow = 1 Turbulent/transitional flow |
| IENRGY | 5-6 | Wall heat transfer option IENRGY = 0 Specify wall temperature = 1 Specify wall heat flux |
| LINIT | 7-8 | X1 = 0 inflow boundary LINIT = 0 Local similarity start = 1 Incompressible flat plate start = 2 Incompressible stagnation start = 3 Input profiles (not Programmed) |
| KINIT | 9-10 | X2 = 0 inflow boundary KINIT = 0 Local similarity start = 1 Plain of symmetry start = 2 Input profiles (not programmed) |
| NITVC | 11-12 | Max. no. iterations (recommended 20) |

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| | | |
|------|-------|--|
| CONV | 21-30 | Convergence tolerance (recommended .0001) |
| AK | 31-40 | Ratio of adjacent step size (recommended 1.05) |
| DN1 | 41-50 | Step size at wall (recommended 0.1) |

Card 3 Gas Properties (5F10.0)

| | | |
|-------|-------|------------------------------------|
| R | 1-10 | Gas constant (air 1716.0) |
| G | 11-20 | Ratio specific heats (air 1.4) |
| PR | 21-30 | Prandtl number (air .72) |
| PRT | 31-40 | Turbulent Prandtl number (air .92) |
| CSTAR | 41-50 | Sutherland's constant (air 198.6) |

Card 4 Flow Conditions (4F10.0)

| | | |
|-------|-------|--|
| XMA | 1-10 | Reference Mach number |
| TFS | 11-20 | Reference static temperature (deg. R.) |
| PFS | 21-30 | Reference static pressure (psf) |
| XLREF | 31-40 | Reference length (ft) |

Card 5 Virtual origin/heat flux conditions (4F10.0)

| | | |
|-------|-------|--|
| X0 | 1-10 | X1 virtual origin (recommended > .0001) |
| W0 | 11-20 | X2 virtual origin (recommended .0000) |
| RHWIN | 21-30 | Wall temperature ratio (T_w/T_{ref}) |
| QWSIN | 31-40 | Wall heat flux ($ftlb/ft^{**2}/sec$) |

Card 6 Transition points (3F10.0)

| | | |
|------|-------|---|
| XT1 | 1-10 | Beginning of transition |
| XT2 | 11-20 | End of transition |
| CISO | 21-30 | Cross flow eddy viscosity parameter CISO = 1.0 isotropic turbulence = 0.4 nonisotropic turbulence |

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Card(s) 7 Print output station numbers (16I5)

LPRO(L) Load up to 16 numbers

KPRO(K) Load up to 16 numbers

KPT Unit 16 print parameter 1<KPT<IWEND

5.2 Output Format

The output for the BL3D code echoes the input data, lists the computational coordinates, prints certain calculated terms, and prints the calculated solution at selected output (L,K) points. The output description is given on the following pages.

Unit 7 Output (file name OUTPUT)

Title Card

72 alphanumeric characters

Echo Input Data

| | |
|-------------------|--|
| IE | Maximum number of points in boundary layer normal direction (in X3) |
| IWEND | Maximum number of points in spanwise direction (in X2) |
| IXEND | Maximum number of points in streamwise direction (in X1) |
| KSTOP | Maximum number of spanwise points at which boundary layer calculation is performed |
| LSTOP | Maximum number of streamwise points at which boundary layer calculation is performed |
| IGBAR = 0 = 1 | Turbulent Levy-Lees variables are used Laminar Levy-Lees variables are used |
| ITURB = 0 = 1 | Turbulent flow (transitional) Laminar flow |
| IENRGY = 0 = 1 | Heat flux specified at the wall Temperature specified at the wall |
| NITCV | Maximum number of iterations permitted at each station |

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| | | |
|-------|------------------|---|
| CONV | | Maximum error permitted in F2N at the wall |
| XMA | M_{∞} | Freestream Mach number |
| TFS | t_{∞} | Freestream static temperature (degrees Rankine) |
| PFS | p_{∞} | Freestream static pressure (psf) |
| R | R | Gas constant (ft**2/sec**2-degree Rankine) |
| G | γ | Ratio of specific heats |
| PR | P_r | Prandtl number |
| PRT | P_{rT} | Turbulent Prandtl number |
| CSTAR | C^* | Constant in Sutherland's viscosity law (degree Rankine) |
| AK | | Ratio of adjacent step sizes in boundary layer direction |
| DN1 | | Step size at the wall in boundary layer |
| XLREF | l | Reference length in feet |
| XT1 | X_{T1} | Beginning of transition in X1 direction |
| XT2 | X_{T2} | End of transition in X1 direction |
| CISO | C_o | Constant used for scaling eddy viscosity in cross flow momentum equation for nonisotropic turbulent flows |
| DXV | ΔX_1 | Step size array in streamwise direction |
| DWV | ΔX_2 | Step size array in spanwise direction |
| XO | X_{10} | X1 location at first streamwise location |
| WO | X_{20} | X2 location at first spanwise location |
| RHWIN | H_w/H_{∞} | Enthalpy ratio at the wall |
| QWSIN | Q_w | Heat flux at the wall |
| LPRO | | Controls print in the streamwise direction |

KPRO Controls print in the spanwise direction

LINIT Initial conditions; option at L=1
 LINIT = 0 Local similarity
 = 1 Incompressible flat plate
 = 2 Incompressible stagnation line
 = 3 Input profiles

KINIT Initial conditions option at K=1
 KINIT = 0 Local similarity
 = 1 Plane of symmetry
 = 2 Input profiles

Calculated Reference Parameters

| | | |
|--------|-----------------|--|
| UFS | U_{∞} | Reference freestream velocity (ft/sec) |
| ROFS | ρ_{∞} | Reference freestream density (slug/ft**3) |
| AMUFS | μ_{∞} | Reference freestream viscosity (slug/ft/sec) |
| REFS | $R_{e\infty}$ | Reference freestream Reynolds number |
| TREF | t_{ref} | Reference temperature (deg. Rankine) |
| AMURF | μ_{ref} | Reference viscosity (slug/ft/sec) |
| RE | R_e | Reference Reynolds number |
| CPRIME | C' | Normalized Sutherland's constant |

Calculated Local Parameters at point (L,K)

These parameters are referenced to an intrinsic coordinate system composed of the boundary layer edge freestream direction and the cross flow (perpendicular) direction. In addition, certain parameters are referenced to their projections onto the $Y_3 = 0$ plane. Parameters in the intrinsic coordinate system are labeled (intr.). Parameters in the Cartesian coordinate system are labeled

(Cart.). Length scales are normalized with respect to the reference length XLREF and velocities are normalized with respect to the reference freestream velocity UFS.

| | | |
|----------|----------------|---|
| X1/L | X_1 | X1 coordinate |
| X2/L | X_2 | X2 coordinate |
| Y1/L | Y_1 | Y1 Cartesian coordinate or |
| S1/L | S_1 | S1 arc length distance |
| Y2/L | Y_2 | Y2 Cartesian coordinate or |
| S2/L | S_2 | S2 arc length distance |
| Y3/L | Y_3 | Y3 Cartesian coordinate |
| CFS | C_{fs} | Streamwise wall friction coefficient (intr.) $2\tau_s/(\rho_e U_e^2)$ |
| CFC | C_{fc} | Crossflow wall friction coefficient (intr.) $2\tau_c/(\rho_e U_e^2)$ |
| QW | Q_w | Wall heat flux |
| ST | S_T | Stanton number ($Q_w/(T_a - T_w)$) |
| TWAD/TFS | T_a/T_∞ | Adiabatic wall temperature ratio |
| UTE | U_{Te} | Total freestream velocity |
| ALPW | α_w | Limiting streamline flow angle (intr.) |
| BET1 | β_1 | } Characteristic directions (intr.) |
| BET2 | β_2 | |
| CP | C_p | Pressure coefficient |
| V1E | V_{1e} | V1 velocity component (Cart.) |

| | | |
|--------|-----------------|---|
| V2E | V_{2E} | Y2 velocity component (Cart.) |
| BETAE | β_e | Boundary layer edge flow direction (Cart.) |
| BETAW | β_w | Limiting wall streamline direction (Cart.) |
| YEDGE | δ | Boundary thickness |
| DELS | δ_S^* | Streamwise displacement thickness (intr.) |
| DELC | δ_C^* | Crossflow displacement thickness (intr.) |
| DELUS | δ_{US}^* | Streamwise velocity thickness (intr.) |
| DELUC | δ_{UC}^* | Crossflow velocity thickness (intr.) |
| THETSS | θ_{SS} | Streamwise momentum thickness (intr.) |
| THETCC | θ_{CC} | Crossflow momentum thickness (intr.) |
| THETSC | θ_{SC} | $U_C \Delta U_S$ momentum thickness (intr.) |
| THETCS | θ_{CS} | $U_S \Delta U_C$ momentum thickness (intr.) |
| THETHS | θ_{HS} | Streamwise enthalpy thickness (intr.) |
| THETHC | θ_{HC} | Crosswise enthalpy thickness (intr.) |
| THETDS | θ_{DS} | Streamwise dissipation thickness (intr.) |
| THETDC | θ_{DC} | Crosswise dissipation thickness (intr.) |
| U1E | U_{1e} | X1 component of edge velocity |
| U2E | U_{2e} | X2 component of edge velocity |
| TW/TFS | T_w/T_∞ | Wall temperature ratio |
| IEDGE | | Index for boundary layer edge |

Calculated profiles at the point (L,K)

The following variables are referenced to the intrinsic coordinate system and are normalized to the local boundary layer edge conditions.

| | | |
|--------|-----------------------------|--------------------------------|
| ZETA3 | ξ_3 | Levy-Lees normal coordinate |
| X3/L | X_3 | Normal distance from wall |
| US/UTE | U_S/U_{Te} | Streamwise velocity ratio |
| UC/UTE | U_C/U_{Te} | Crossflow velocity ratio |
| UT/UTE | U_T/U_{Te} | Total velocity ratio |
| ALPC | α_c | Flow angle (deg) |
| T/TE | T/T_e | Static temperature ratio |
| VIS | $(\rho \mu)/(\rho_e \nu_e)$ | Levy-Lees stretching parameter |

5.3 Input/Output Data Files

The input data files are units 10, 11, 12 which are read by the main program MAIN. The output data files are units 13, 15, and 16. Unit 20 serves as both an input and output temporary file. The data on units 10, 11, 12 are written by the SETUP code or the user may setup this data independently. The data on units 13, 15, 16, and 20 are written by subroutine ROUTPT. A detailed description of these files are given below.

Unit 10 (IDRM1) Metric Data

The first set of data on this file is the number of points in the computational mesh. FORMAT(3I5)

| | |
|-------|---------------------------------------|
| IE | Number of points in the X3 direction |
| IXEND | (No. of pts.) - 1 in the X1 direction |
| IWEND | (No. of pts.) - 1 in the X2 direction |

The second set of data is IXEND X1 coordinate differences and IWEND X2 coordinate differences. FORMAT(7E14.7)

| | |
|------------------|--------------------------|
| DXV(L),L=1,IXEND | X1 coordinate difference |
| DWV(K),K=1,IWEND | X2 coordinate difference |

The final set of data consists of the metric data for each mesh point (L,K) having a FORMAT(7E14.7/7E14.7). This data is arranged to be read by a DO K LOOP nested within a DO L LOOP. At each mesh point (L,K) the following data is read.

| | | |
|-----------|----------------------------------|-----------------------------------|
| H1(K) | H_1 | X1 metric scale coefficient |
| H2(K) | H_2 | X2 metric scale coefficient |
| DH1DX(K) | $\partial H_1 / \partial X_1$ | $D(H1)/DX1$ |
| DH1DW(K) | $\partial H_1 / \partial X_2$ | $D(H1)/DX2$ |
| DH2DX(K) | $\partial H_2 / \partial X_1$ | $D(H2)/DX1$ |
| DH2DW(K) | $\partial H_2 / \partial X_2$ | $D(H2)/DX2$ |
| G12(K) | G_{12} | Covariant metric tensor component |
| GM(K) | $ G $ | Determinant of metric tensor |
| DG12DX(K) | $\partial G_{12} / \partial X_1$ | $D(G12)/DX1$ |
| DG12DW(K) | $\partial G_{12} / \partial X_2$ | $D(G12)/DX2$ |
| RAD(K) | R | Radius |
| DRADX(K) | $\partial R / \partial X_1$ | $D(R)/DX1$ |
| DRADW(K) | $\partial R / \partial X_2$ | $D(R)/DX2$ |
| OMEGA3(K) | Ω_3 | Vorticity normal to the surface |

Unit 11 (IDRM2) Boundary Layer Edge Data

The data on this file consists of the boundary layer edge conditions for each computational point (L,K). This data, like the data above, is read by a DO K LOOP nested in a DO L LOOP. At each mesh point (L,K) the following data is read. FORMAT(7E14.7/1E14.7).

| | | |
|---------|----------------------------------|-----------------------|
| U(K) | U_{1e} | X1 velocity component |
| V(K) | U_{2e} | X2 velocity component |
| PP(K) | P | Static pressure |
| DUDW(K) | $\partial U_{1e} / \partial X_2$ | $D(U1)/DX2$ |

DVDW(K) $\partial U_{2e}/\partial X_2$ D(U2)/DX2

DUDX(K) $\partial U_{1e}/\partial X_1$ D(U1)/DX1

DVDX(K) $\partial U_{2e}/\partial X_2$ D(U2)/DX2

HR(K) Rothalpy

Unit 12 (IDRM3) Direction Cosine Data

The data on this file consists of the direction cosines for each computational point (L,K). This data is read by a DO K LOOP nested in a DO L LOOP. At each mesh point the following data is read. FORMAT(7E14.7/5E14.7).

Y1 Y₁ Y1 Cartesian coordinate or
S1 S₁ S1 arc length along X1

Y2 Y₂ Y2 Cartesian coordinate or
S2 S₂ S2 arc length along X2

Y3 Y₃ Y3 Cartesian coordinate

((GAM(I,J,K),J=1,3),I=1,3) Direction cosines

Unit 13 (IDRM4) Crossection Plotting Data

The following data is output for each mesh point (L,K) by a DO K LOOP nested in a DO L LOOP. FORMAT(2I3,9E12.5).

K X2 index

L X1 index

Y1(K) Y₁ Y1 Cartesian coordinate or

S1(K) S₁ X1 arc length

VCAP U_{1e} X1 edge velocity

CVCAP U_{2e} X2 edge velocity

| | | |
|--------|---------------|-----------------------------------|
| CP | C_p | Static pressure coefficient |
| DELS | δ^*_S | Streamwise displacement thickness |
| DELC | δ^*_C | Crossflow displacement thickness |
| THETSS | θ_{SS} | Streamwise momentum thickness |
| THETCC | θ_{CC} | Crossflow momentum thickness |
| ST | S_T | Stanton number |

Unit 15 (IDRM5) Contour and Vector Plotting Data

The following data is output for each mesh point (L,K) by a DO K LOOP nested in a DO L LOOP. FORMAT(2I3,9E12.5)

| | | |
|--------|-----------------|---------------------------------------|
| K | | X2 index |
| L | | X1 index |
| Y1 | Y_1 | Y1 Cartesian coordinate or |
| S1 | S_1 | S1 arc length along X1 |
| Y2 | Y_2 | Y2 Cartesian coordinate or |
| S2 | S_2 | S2 arc length along X2 |
| Y3 | Y_3 | Y3 Cartesian coordinate |
| CFS | C_{fs} | Streamwise friction coefficient |
| CFC | C_{fc} | Crossflow friction coefficient |
| U1E | U_{1e} | Y1 Cartesian component of velocity or |
| V1E | V_{1e} | X1 component of velocity |
| U2E | U_{2e} | Y2 Cartesian component of velocity or |
| V2E | V_{2e} | X2 component of velocity |
| EPS1W | ϵ_{1w} | Y1 Cartesian component of strain or |
| F2N(1) | e_{1w} | X1 component of strain |

| | | |
|--------|-----------|-------------------------------------|
| EPS2W | E_{210} | Y2 Cartesian component of strain or |
| G2N(1) | e_{2w} | X2 component of strain |

Unit 16 (IDRM6) Special Crossection data

The following data is output for each mesh point (L,KPT) where KPT is an input parameter. FORMAT(2I3,9E12.5).

| | | |
|------|----------|---------------------------------|
| K | | X2 index |
| L | | X1 index |
| Y1 | Y_1 | Y1 Cartesian coordinate or |
| S1 | S_1 | S1 arc length along X1 |
| CFS | C_{fs} | Streamwise friction coefficient |
| ST | S_t | Stanton number |
| TW | T_w | Wall temperature |
| TWAD | T_a | Adiabatic wall temperature |
| STE | S_{te} | Local Stanton number |

Unit 20 (IDRM7) Wall Temperature Data

The following data is output/input for each mesh point (L,K) in a DO K LOOP nested in a DO L LOOP. If QW = 0, The wall temperature is the adiabatic wall temperature and is output onto file 20. If QW > 0, the adiabatic wall temperature is read from file 20. FORMAT(E12.5).

| | | |
|---------|-------|----------------------------|
| TW,TWAD | T_a | Adiabatic wall temperature |
|---------|-------|----------------------------|

5.4 Diagnostics

A number of checks are made during the course of the calculation. If a minor error occurs, a DIAGNOSTIC message is printed and the calculation is continued. If a serious error occurs, a DIAGNOSTIC message is printed and the calculation stops. A description of the DIAGNOSTIC messages is given below.

1) NEGATIVE TEMPERATURE DETECTED IN MOLVIS AT K=

where K is the spanwise station where the error is detected. This error is detected in subroutine MOLVIS and indicates that a negative temperature is calculated in MOLVIS. This negative temperature only occurs if the iteration at the (L,K) mesh point does not converge. The usual problem is that negative spanwise velocities occur at this spanwise station producing instabilities. The calculation is continued by indexing L to the next streamwise station.

5.5 Sample Input

A sample input to the BL3D code is given below card by card as described in Sect. 5.1. To assist the user in setting up a new case comments are inserted between blocks of data in lower case letters. These comments of course should not be on the input cards.

Card 1 Title card (load 72 alphanumeric characters)

GAS TURBINE CASCADE - ROTATING PRESSURE SURFACE

Card 2 Option Card (6I2,8X,3F10.0)

1 1 1 0 020 .0001 1.05 0.10

Card 3 Gas Properties (5F10.0)

1716.0 1.4 0.72 0.95 198.6

Card 4 Flow Conditions (4F10.0)

.0985114 519.0 2117.0 0.9233

Card 5 Virtual origin/heat flux conditions (4F10.0)

00.1000 .000 1.0 000.0

Card 6 Transition points (3F10.0)

00.1002 00.1003 1.0

Card(s) 7 Print output station numbers (16I5)

1 5 18 29 39 40

1 10 20 30 40

6.0 DESCRIPTION OF SETUP CODE

6.1 SETUP Main Program

The main program for the SETUP code opens and closes all input and output files and calls the subroutines which execute the primary tasks depending on the input options IOPT1 through IOPT12. An overall view of the SETUP code is shown on the Global Tree Structure Chart shown on the following pages. This tree structure is arranged by tasks and labeled as they appear in the main program SETUP. Column 1 shows the main program which calls the subroutines in column 2. Each subroutine in column 2 executes a major task and calls the subroutine in column 3. For any given calculation not all branches of the tree are called.

Chart I Global Tree Structure by Task

| | | | | |
|-------|---|---|---|--|
| SETUP | | | | |
| 1.0 | Read Input Data | | | |
| | INPDAT | | | |
| 2.0 | Setup Reference Conditions | | | |
| | REFCON | | | |
| 3.0 | Setup Pressure Distribution | | | |
| | ROTORP | | | |
| 4.0 | Calculate Rotor Inlet Conditions | | | |
| | RINLET | | | |
| 5.0 | Smooth Pressure Distribution Data | | | |
| | SMTHD | INTR1D INTR2D | | |
| 6.0 | Echo Input Data | | | |
| | OPTDAT | | | |
| 7.0 | Compute Metric Data and B. L. Edge Conditions | | | |
| | SOLVE | INTRB INTRC METCO DIRCOS ROTOR INTRD BLEDGE | LAG4PT LAG4PT SPLINE EVAL INTR1D INTR3D INTREK INTREL UITER | |

6.2 SETUP COMMON Block Variables

PARAMETERS

| | | |
|-------|-------|--|
| LPL | (101) | Max. no. X_1 mesh points |
| KPL | (61) | Max no. X_2 mesh points |
| LBL | (51) | Max. no. input X_1 boundary points |
| KBL | (51) | Max. no. input X_2 boundary points |
| LSL | (51) | Max. no. input X_1 surface points |
| KSL | (51) | Max. no. input X_2 surface points |
| LDL | (21) | Max. no. input X_1 inflow points |
| KDL | (21) | Max. no. input X_2 inflow points |
| IDRM1 | 8 | Output unit for metric data |
| IDRM2 | 9 | Output unit for edge conditions |
| IDRM3 | 10 | Output unit for transformation variables |
| IDRM4 | 11 | Output unit for length scales |
| IDRM5 | 12 | Output unit for setup code |

COMMON /INTV/ Integer Variables

| | |
|--------|------------------------------------|
| LPLAST | No. input X_1 mesh points |
| KPLAST | No. input X_2 mesh points |
| LSLAST | No. input X_1 surface points |
| KSLAST | No. input X_2 surface points |
| LBLAST | No. input X_1 boundary points |
| KBLAST | No. input X_2 boundary points |
| LDLAST | No. output X_1 C_p data points |

| | |
|--------|------------------------------------|
| KDLAST | No. output X_2 C_9 data points |
| LULAST | No. input X_1 inflow points |
| KULAST | No. input X_2 inflow points |
| LILAST | No. input X_1 C_p data points |
| KILAST | No. input X_2 C_p data points |

COMMON /IOPT/ Input Options

| | |
|--------|----------------------------|
| IOPT1 | Surface geometry option |
| IOPT2 | Grid boundary option |
| IOPT3 | Pressure data input option |
| IOPT4 | Mesh distribution option |
| IOPT5 | Inflow option |
| IOPT6 | Print option |
| IOPT7 | Pressure smoothing option |
| IOPT8 | Rotor/Stator option |
| IOPT9 | Coordinate output option |
| IOPT10 | Relative eddy option |
| IOPT11 | Upstream inflow option |
| IOPT12 | Not used |

COMMON /INDV/ Independent Variables

| | | |
|-------|-----------|------------------------|
| X1(L) | X_1^L | X_1 coordinate array |
| X2(K) | $X_{2,K}$ | X_2 coordinate array |

| | | |
|--------|------------------|------------------|
| DX1(L) | ΔX_1^L | X_1 step size |
| DX2(K) | $\Delta X_{2,K}$ | X_2 step size |
| X1P | X_1 | X_1 coordinate |
| X2P | X_2 | X_2 coordinate |

COMMON /SURFC/ 2D Coordinate Surface Variables

| | | |
|---------|----------------------|--------------------------------------|
| YY(LK) | Y_1^L or $Y_{2,K}$ | Y_1 or Y_2 Cartesian coordinates |
| YY3(LK) | $Y_{3,K}^L$ | Y_3 Cartesian coordinate |

COMMON /SMIX/ 3D Coordinate Surface Variables

| | | |
|----------|-------------|---------------------------------------|
| Y1M(L) | Y_1^L | Y_1 Cartesian coordinate of surface |
| Y2M(K) | $Y_{2,K}$ | Y_2 Cartesian coordinate of surface |
| Y3M(L,K) | $Y_{3,K}^L$ | Y_3 Cartesian coordinate of surface |

COMMON /ARCL/ Arc Length Variables

| | | |
|--------|-----------|--------------------------------|
| SS1(K) | $S_{1,K}$ | X_1 arc length array |
| HS1(K) | H_{1K} | X_1 metric coefficient array |
| SL1 | S_1 | X_1 arc length |
| SL2 | S_2 | X_2 arc length |
| SS10 | S_{10} | X_1 arc length start |

COMMON /COMB/ Computational Boundary Variables

| | |
|-------------------|-----------------------|
| Y10X2(K),Y20X2(K) | Side 1 input boundary |
| Y1X11(L),Y2X11(L) | Side 2 input boundary |
| Y11X2(K),Y21X2(K) | Side 3 input boundary |
| Y1X10(L),Y2X10(L) | Side 4 input boundary |

COMMON /TRANSV/ Transformation Variables

| | | |
|-------------|--|--|
| Y1P,Y2P,Y3P | Y_1, Y_2, Y_3 | Cartesian coordinates |
| DY11 | $\partial Y_1 / \partial X_1$ | First partial derivatives of Cartesian coordinates with respect to surface coordinates |
| DY12 | $\partial Y_1 / \partial X_2$ | |
| DY21 | $\partial Y_2 / \partial X_1$ | |
| DY22 | $\partial Y_2 / \partial X_2$ | |
| DY31 | $\partial Y_3 / \partial X_1$ | |
| DY32 | $\partial Y_3 / \partial X_2$ | |
| D2Y111 | $\partial^2 Y_1 / \partial X_1 \partial X_1$ | Second partial derivatives of Cartesian coordinates with respect to surface coordinates |
| D2Y112 | $\partial^2 Y_1 / \partial X_1 \partial X_2$ | |
| D2Y122 | $\partial^2 Y_1 / \partial X_2 \partial X_2$ | |
| D2Y211 | $\partial^2 Y_2 / \partial X_1 \partial X_1$ | |
| D2Y212 | $\partial^2 Y_2 / \partial X_1 \partial X_2$ | |
| D2Y222 | $\partial^2 Y_2 / \partial X_2 \partial X_2$ | |
| D2Y311 | $\partial^2 Y_3 / \partial X_1 \partial X_1$ | |
| D2Y312 | $\partial^2 Y_3 / \partial X_1 \partial X_2$ | |
| D2Y322 | $\partial^2 Y_3 / \partial X_2 \partial X_2$ | |

COMMON /METRIC/ Metric variables

| | | |
|------------------|----------|--|
| GL11, GL12, GL13 | G_{ij} | Covariant metric tensor components |
| GL21, GL22, GL23 | | |
| GL31, GL32, GL33 | | |
| GU11, GU12, GU13 | G^{ij} | Contravariant metric tensor components |
| GU21, GU22, GU23 | | |
| GU31, GU32, GU33 | | |

| | | |
|--|--|------------------------------------|
| DG | G | Determinate of metric tensor |
| HH1,HH2,HH3 | H ₁ ,H ₂ ,H ₃ | Metric scale coefficients |
| DH11 | ∂H ₁ /∂X ₁ | Derivatives of metric scale coeff. |
| DH12 | ∂H ₁ /∂X ₂ | |
| DH21 | ∂H ₂ /∂X ₁ | |
| DH22 | ∂H ₂ /∂X ₂ | |
| DG121 | ∂G ₁₂ /∂X ₁ | Derivatives of metric tensor |
| DG122 | ∂G ₁₂ /∂X ₂ | |
| COMMON /DIRC/ Direction cosines | | |
| GAM(I,J) | γ _{ij} | Direction cosines |
| GAMI(I,J) | γ _{ij} ⁻¹ | Inverse of direction cosines |
| COMMON /INPEDG/ Pressure Distributions Variables | | |
| Y1D(L) | Y ₁ ^L | Output Y coordinate |
| Y2D(K) | Y _{2,K} | Output Y coordinate |
| Y3D(L,K) | C _{p,K} ^L | Output pressure coeff. |
| Y1I(L) | Y ₁ ^L | Input Y coordinate |
| Y2I(K) | Y _{2,K} | Input Y coordinate |
| Y3I(L,K) | C _{p,K} ^L | Input pressure coeff |
| COMMON /BLEDGE/ Boundary Edge Variables | | |
| U1E | U _{1e} | X ₁ Edge velocity |
| U2E | U _{2e} | X ₂ Edge velocity |

| | | |
|----------------------------------|--------------------------------|------------------------------|
| PP | P | Edge static pressure |
| DU1DX1 | $\partial U_{1e}/\partial X_1$ | Edge velocity gradients |
| DU1DX2 | $\partial U_{1e}/\partial X_2$ | |
| DU2DX1 | $\partial U_{2e}/\partial X_1$ | |
| DU2DX2 | $\partial U_{2e}/\partial X_2$ | |
| CP | C_p | Static pressure coefficient |
| DCPDX1 | $\partial C_p/\partial X_1$ | Static pressure gradients |
| DCPDX2 | $\partial C_p/\partial X_2$ | |
| ERROR | ϵ | |
| DU1DX | $\partial U_{1e}/\partial X_1$ | Explicit velocity gradients |
| DU2DX | $\partial U_{2e}/\partial X_1$ | |
| HR | I | Edge rothalpy |
| COMMON /INFLO/ Inflow Conditions | | |
| U2X2(K) | $U_{2e,K}$ | Side 1 input inflow velocity |
| U2X1(L) | U_{2e}^L | Side 4 input inflow velocity |
| YI2U(K) | $Y_{2,K}$ | Side 1 input coordinate |
| YI1U(L) | Y_1^L | Side 4 input coordinate |
| COMMON /UBLED/ Stored arrays | | |
| U1(K) | $U_{1e,K}$ | X_1 velocity array |
| U2(K) | $U_{2e,K}$ | X_2 velocity array |
| CPD(K) | $C_{p,K}$ | Pressure coefficient |
| ROTHLP(K) | I_K | Rothalphy |

COMMON /GASP/ Constants

| | | |
|------|----------|-------------------------|
| GASR | R | Gas constant |
| GAMM | γ | Ratio of specific heats |
| TI | | 0.01745329 |
| PI | | 3.1415926 |

COMMON /FLOWI/ Input Flow Conditions

| | | |
|--------|-------------------|--|
| PINFI | P_{∞} | Reference static pressure |
| TINFI | t_{∞} | Reference free stream static temperature |
| ROINFI | ρ_{∞} | Reference density |
| UINFI | u_{∞} | Reference velocity |
| XMINFI | M_{∞} | Reference mach number |
| BET1I | $\beta_{1\infty}$ | Not used |
| XLREF | l | Reference length |

COMMON /FLOWV/ Output Flow Conditions

| | | |
|--------|----------------|---|
| PINF | P_{∞} | Reference static pressure |
| TINF | T_{∞} | Reference freestream static temperature |
| TREF | T_{ref} | Reference temperature |
| HINF | H_{∞} | Reference enthalpy |
| PINFL | P_L | Rotor inlet static pressure |
| HRINFL | I_L | Rotor inlet enthalpy |
| DHINF | ΔH | Side 4 delta enthalpy |
| ALP1I | α_{100} | Not used |

COMMON /FLOWU/ Output Flow Variables

| | | |
|--------|---------------------|-------------------------------------|
| PTABSF | $\bar{P}_{T\infty}$ | Absolute total pressure |
| HTABSF | $\bar{T}_{T\infty}$ | Absolute total enthalpy |
| PTABSL | \bar{P}_{TL} | Absolute rotor inlet total pressure |

COMMON /ROTOR/ Input Rotor Parameters

| | | |
|---------------|---------------|--|
| VBTI | V_{Bt} | Rotor tip velocity |
| G01,G02,G03 | γ_{oi} | Direction cosines for vorticity vector |
| RADHI,RADTI | R_H, R_T | Hub/Tip radius |
| YRADHI,YRADTI | Y_H, Y_T | Hub,Tip coordinates |
| GAPI | G | Rotor midspan gap |

COMMON /ROTOR1/ Output Rotor Parameters

| | | |
|-------------------|-----------------------------|---|
| OMEG1,OMEG2,OMEG3 | Ω_i | Vorticity components in Cartesian coor. |
| RAD | R | Radius |
| DRAD1 | $\partial R / \partial X_1$ | Derivatives |
| DRAD2 | $\partial R / \partial X_2$ | |

COMMON /ROTOR2/ Rotor Inlet Parameters

| | | |
|--------|------------------|-------------------------------------|
| VBINF | $V_{B\infty}$ | Rotor blade reference velocity |
| UPINF | $U_{\phi\infty}$ | Rotor reference tangential velocity |
| VBINFL | V_{BL} | Rotor blade inlet velocity |
| UPINFL | $U_{\phi L}$ | Rotor inlet tangential velocity |
| SGNR | $(+/-)_U$ | Sign on radius vector |
| SGNU | $(+/-)_L$ | Sign on rotor tangential velocity |
| DELCF | ΔC_p | Rotor CP correction |

COMMON /UPSTR1/ Input Upstream Flow Variables

| | | |
|---------|-----------|-------------------------------------|
| Y2RI(K) | $Y_{2,K}$ | Y_2 input coordinate |
| PTRI(K) | $P_{T,K}$ | Upstream absolute total pressure |
| TTRI(K) | $T_{T,K}$ | Upstream absolute total temperature |

COMMON /UPSTR2/ Input Upstream Flow Variables

| | | |
|---------|---------------|------------------------------|
| UZRI(K) | $U_{z,K}$ | Upstream axial velocity |
| BTRI(K) | $\beta_{1,K}$ | Upstream relative flow angle |

COMMON /UPSTR3/ Output Upstream Flow Variables

| | | |
|--------|--------------|--------------------------------------|
| U1A(K) | $U_{1,K}$ | Absolute total velocity |
| UPA(K) | $U_{\phi,K}$ | Absolute tangential velocity |
| U1R(K) | $U_{1,K}$ | Relative total velocity |
| UPR(K) | $U_{\phi,K}$ | Relative tangential velocity |
| U2S(K) | $U_{2s,K}$ | Est. initial rotor spanwise velocity |

COMMON /UPSTR4/ Output Upstream Flow Variables

| | | |
|--------|----------------|--------------------------------------|
| UZA(K) | $U_{z,K}$ | Absolute axial velocity |
| VBB(K) | $V_{B,K}$ | Rotor velocity |
| BTA(K) | β_K | Absolute inlet flow angle |
| OMS(K) | $\Omega_{S,K}$ | Ratio relative vorticity/rotor speed |
| RDK(K) | R_K | Rotor radius |

COMMON /UPSTR5/ Output Upstream Flow Variables

| | | |
|--------|-----------|----------------------------------|
| PS(K) | P_K | Rotor inlet static pressure |
| TS(K) | T_K | Rotor inlet static temperature |
| HTA(K) | H_K | Absolute inlet total enthalpy |
| PTA(K) | $P_{T,K}$ | Absolute inlet total pressure |
| TTA(K) | $T_{T,K}$ | Absolute inlet total temperature |

6.3 Description of SETUP Subroutines

| | |
|--------|---|
| BLEDGE | Integrate boundary layer edge eqs. |
| CUBA | See subroutine CUBTWO |
| CUBB | See subroutine CUBTWO |
| CUBTWO | Calculate two dimensional cubic spline fit |
| DIRCOS | Calculate direction cosines and inverse |
| EVAL | Evaluate function and derivatives of spline fit |
| INPDAT | Read input data |
| INTRB | Establish the mapping of the boundaries |
| INTRC | Establish surface geometry |
| INTRD | Calculate pressure coeff. and derivatives |
| INTREK | Interpolate inflow velocity on L=1 boundary |
| INTREL | Interpolate inflow velocity on K=1 boundary |
| INTR1D | Linear interpolation on 1d grid |
| INTR3D | Linear interpolation on 2d grid |
| LAG4PT | Lagrangian 4 point interpolation |
| MATRIX | See subroutine CUBTWO |
| METCO | Calculate metric data |
| OPEC | Calculate one sided proximate end conditions |
| OPTDAT | Echo input data |
| PERM | See subroutine CUBTWO |

| | |
|--------|---|
| REFCON | Setup reference conditions |
| RINLET | Calculate rotor inlet conditions |
| ROTOR | Estimate upstream total enthalpy and pressure |
| ROTORP | Setup pressure distribution for relative eddy approx. |
| SETUP | Main program |
| SMTHD | Smooth input CP data |
| SOLVE | Compute metric data and b. l. edge conditions |
| SPLINE | Setup derivatives on boundary for surface spline fit |
| UITER | Iteration algorithm for U1E , U2E |

Subroutine BLEDGE(L,K)

Object

This subroutine integrates the boundary layer edge equations using the input pressure (CP) distribution. The boundary layer edge equations are solved at the point X1, X2 for the velocities U1E, U2E and the enthalpy HE for the given input static pressure.

Options

IOPT3 = 0 No pressure data
 = 1 CP = CP(X1,X2)
 = 2 CP = CP(Y1,Y2)
 = 3 CP = CP(Y1,X2)
 = 4 CP = CP(X1,Y2)
 = 5 Analytical pressure data

IOPT5 = 0 U2E = 0.0 ; U1E calculated from the Euler equation
 = 1 U2E(0,X2) = 0.0 ; U2E(X1,0) = 0.0
 = 2 U2E(0,X2) = 0.0 ; U2E(X1,0) input
 = 3 U2E(0,X2) input ; U2E(X1,0) = 0.0
 = 4 U2E(0,X2) input ; U2E(X1,0) input

List of Symbols

| | |
|-----------|---------------------------------|
| A0 to A10 | Coefficients of edge equations |
| C1 to C6 | Coefficients of edge equations |
| D1 to D6 | Coefficients of Euler equations |
| E1 to E3 | Coefficients of energy equation |
| L, K | Index for X1 and X2 |

Theory

The basic equations are described in Sect. 3.11 of Ref 1. This subroutine first calculates the coefficients of the differential equations. Then it determines if the point L, K is on an inflow boundary (L=1) or (K=1) or an interior point.

If L=1 and IOPT5 = 1 or 2 ; U2E = 0

If L=1 and IOPT5 = 1 or 2 ; U2E is interpolated from the input data using subroutine INTREK

If K=1 and IOPT5 = 3 or 4 ; U2E = 0

If K=1 and IOPT5 = 3 or 4 ; U2E is interpolated from the input data using subroutine INTREL

IF L>1 and K>1 ; U2E and U2E are calculated by integrating the boundary layer edge equations

After U1E, U2E and HE are calculated, all the remaining boundary edge variables required by the BL3D code are then calculated.

References

1. Anderson, O. L. : Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.

Subroutine CUBTWO(Arg. List)

Object

This subroutine performs a two dimensional cubic spline fit to unequally spaced data.

Options

None

List of Symbols

| | |
|------------|---------------------|
| N | Max. X array size |
| M | Max. Y array size |
| X(I) | Input Y1 coordinate |
| Y(J) | Input Y2 coordinate |
| U(I,J) | Input Y3 coordinate |
| P(I,J) | DY3/DY1 |
| Q(I,J) | DY3/DY2 |
| R(I,J) | D2Y3/DY1/DY2 |
| A(I,J,K,L) | Spline coefficients |
| CDX | Work arrays |
| DY | |
| ZX | |
| ZY | |
| ORD | |
| UNB | |
| F | |

Theory

This subroutine performs a two dimensional cubic spline fit to the input blade surface using the theory of Ref. 1. This subroutine is called by subroutine SPLINE, and calls subroutines PERM , MATRIX , CUBA , and CUBB.

References

1. Spath, H. : Spline Algorithms for Curves and Surfaces, Utilitas Mathematica Publishing Co. Inc., Winnipeg, 1974.

Subroutine DIRCOS

Object

This subroutine calculates the direction cosine tensor and the inverse of the direction cosine tensor for the transformation from the computational to the Cartesian coordinates

Options

None

List of Symbols

See COMMON blocks

Theory

The theory for calculating the direction cosine tensor is given in Sect. 3.10 by Anderson (Ref.1).

References

1. Anderson, O. L. : Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.

Subroutine EVAL(Arg. List)

Object

This subroutine evaluates $Y_3, DY_3/DY_1, DY_3/DY_2, D^2Y_3/DY_1/DY_1, D^2Y_3/DY_2/DY_2, -$
 $D^2Y_3/DY_1/DY_2$ at the point (Y_1P, Y_2P) using the Spline coefficients calculated in
subroutine SPLINE.

Options

None

List of Symbols

| | |
|-----------------------|-----------------------|
| A(I,J,K,L) | Spline coefficients |
| LL1 | No. Y1 input points |
| KK1 | No. Y2 input points |
| LSI | Corner point Y1 index |
| KSI | Corner point Y2 index |
| DY3Y1 DY3/DY1 | First derivatives |
| DY3Y2 DY3/DY2 | |
| DY3Y11 D2Y3/DY1/DY1 | |
| DY3Y12 D2Y3/DY1/DY2 | Second derivatives |
| DY3Y22 D2Y3/DY2/DY2 | |

Theory

The function and its derivatives are evaluated using the formulas derived in
Ref. 1. For the function we have:

$$Y_3 = \sum_{k=1}^4 \sum_{\ell=1}^4 A_{ijk\ell} (Y_1 - Y_1^i)^k (Y_2 - Y_{2ok})^\ell \quad (1)$$

The partial derivatives are evaluated by analytically differentiating Eq. (1).

References

1. Spath, H.: Spline Algorithms for Curves and Surfaces. Utilitas Mathematica Publishing Co., Inc, Winnipeg, 1974.

Subroutine INPDAT

Object

This subroutine reads all input data for the SETUP code according to the input options IOPT1 through IOPT12

Options

IOPT4 = 0 Uniform (X1,X2) computational grid calculated
IOPT2 = 0 Uniform (Y1,Y2) Cartesian grid calculated
= 1 Skewed (Y1,Y2) grid calculated
= 2 One dimensional mapping using sides 1 and 3
= 3 One dimensional mapping using sides 2 and 4
= 4 Two dimensional mapping

List of Symbols

See COMMON blocks

Theory

This subroutine reads all input data required by the SETUP code and calculates certain grids by default since they do not require all the input data for general grids. See Options List.

Subroutine INTRB

Object

This subroutine establishes the mapping of the physical boundaries to the computational boundaries.

Options

None

List of Symbols

See COMMON block variables

Theory

The theory for this calculation is given by Anderson (Ref. 1). The physical boundaries are known from the input data as ordered pairs of points for the four sides of the physical boundary as shown on Fig. 1. These are given by:

$$\begin{array}{ll}
 Y1(0,X2P),Y2(0,X2P) & \text{KBLAST points for Side 1} \\
 Y1(X1P,1),Y2(X1P,1) & \text{LBLAST points for Side 2} \\
 Y1(1,X2P),Y2(1,X2P) & \text{KBLAST points for Side 3} \\
 Y1(X1P,0),Y2(X1P,0) & \text{LBLAST points for Side 4}
 \end{array} \tag{1}$$

where

$$\begin{array}{l}
 0.0 < X1P < 1.0 \\
 0.0 < X2P < 1.0
 \end{array} \tag{2}$$

Then considering Side 1, we note that the boundary is only a function of $X2P$. Thus the Side 1 boundary can be written in parametric form as a function of $X2P$ by establishing an array $X2B(KB)$ $KB=1, KBLAST$ at equal increments $0.0 < X2B < 1.0$ so that there is a one to one correspondence of points. The same procedure follows for the other three sides. With the boundaries established in parametric form, the Cartesian coordinates $(Y1, Y2)$ of the of the boundary is known as a function of the computational coordinates $(X1P, X2P)$. Given the computational coordinate $(X1P, X2P)$, the corresponding Cartesian coordinates of the boundary on the four sides is obtained by interpolation using the four point Lagrangian interpolation formulas contained in subroutine LAG4PT.

The interior Cartesian coordinate point $(Y1P, Y2P)$ corresponding to the computational coordinate point $(X1P, X2P)$ is obtained by the transfinite mapping of Gorden and Thiel (Ref. 2) as shown in Sect. 3.10 of Ref. 1. With the mapping established, the derivatives of $Y1$ and $Y2$ with respect to $X1$ and $X2$ are obtained by analytically differentiating the algebraic mapping formula. Subroutine LAG4PT also returns the first and second derivatives of the Cartesian coordinates $Y1$ and $Y2$ of the boundaries with respect to the appropriate computational coordinate $X1$ or $X2$ so that the first and second partial derivatives can be obtained.

References

1. Anderson, O. L. : Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.
2. Gorden, J. W. and L. C. Thiel: Transfinite Mapping and Their Application to Grid Generation, Numerical Grid Generation, F. Thompson Ed., Elsevier Publishing Co. Inc. (1982).

Subroutine INTRC

Object

This subroutine establishes the complete surface geometry by calculating the first and second partial derivatives of the surface coordinate Y3 with respect to Y1 and Y2.

Options

| | |
|-----------|-----------------|
| IOPT1 = 0 | Y3 = 0.0 |
| IOPT1 = 1 | Y3 = Y3(Y1) |
| IOPT1 = 2 | Y3 = Y3(Y2) |
| IOPT1 = 3 | Y3 = Y3(Y1, Y2) |

List of Symbols

See COMMON blocks

Theory

The Cartesian coordinate of the surface Y3 and the partial derivatives of Y3 with respect to Y1 and Y2 are obtained by interpolation.

| | |
|-----------|---|
| IOPT1 = 0 | Y3 and all derivatives are zero. |
| IOPT1 = 1 | Y3 and its derivatives are obtained by interpolation |
| = 2 | using a four point Lagrangian interpolation contained in subroutine LAG4PT. |
| IOPT1 = 3 | Y3 and its derivatives are obtained using a surface spline interpolation contained in subroutine EVAL. The spline coefficients are calculated first when L=1 and K=1 by calling subroutine SPLINE. |

Subroutine INTRD

Object

Calculate pressure coefficient CP and derivatives.

Options

IOPT3 = 0 No CP data
IOPT3 = 1 CP = CP(X1,X2)
IOPT3 = 2 CP = CP(Y1,Y2)
IOPT3 = 3 CP = CP(Y1,X2)
IOPT3 = 4 CP = CP(X1,Y2)
IOPT3 = 5 CP Analytical function

List of symbols

AX Logical variable (if TRUE X1P lies on grid line)
AY Logical variable (if TRUE X2P lies on grid line)
ONED Logical variable (If TRUE X1P or X2P lies on grid line)

Theory

The pressure coefficient CP and its derivatives with respect X1 and X2 are calculated in this subroutine. If X1 or X2 lie on a grid line, then CP and its derivatives with respect to the input variables (X1 or Y1) and (X2 or Y2) are calculated using a one dimensional interpolation contained in subroutine INTR1D. If X1 and X2 do not lie on a grid line, then CP and its derivatives with respect to the input variables (X1 or Y1) and (X2 or Y2) are calculated using a linear two dimensional interpolation contained in subroutine INTR3D. Then depending on the option IOPT3, the partial derivatives with respect to the coordinates are calculated.

Subroutine INTREK

Object

This subroutine interpolates for the inflow velocities along the $X1 = 0.0$ boundary.

Options

None

List of Symbols

See COMMON Blocks

Theory

The input arrays are $Y12U(K)$ and $U2X2(K)$. Then given $Y2$, along the $X1 = 0.0$ boundary, the inflow velocity $U2E$ is interpolated from the input arrays using the four point Lagrangian interpolation contained in subroutine LAG4PT.

Subroutine INTREL

Object

This subroutine interpolates for the inflow velocities along the $X2 = 0.0$ boundary.

Options

None

List of Symbols

See COMMON Blocks

Theory

The input arrays are $Y1U(L)$ and $U2X1(L)$. Then given $Y1$, along the $X2 = 0.0$ boundary, the inflow velocity $U2E$ is interpolated from the input arrays using the four point Lagrangian interpolation contained in subroutine LAG4PT.

Subroutine INTR1D

Object

Interpolates between data points which lie on a gridline.

Options

None

List of Symbols

| | |
|-------|--|
| X | Ordinates |
| Y | Abscissa |
| F | Function $F(X,Y)$ |
| L,K | Indices of Interpolation |
| XP,YP | Interpolation Point |
| FP | $F(XP,YP)$ |
| DFDX | $d(F(XP,YP))/dx$ |
| DFDY | $d(F(XP,YP))/dy$ |
| LD,KD | Dimensions: $X(LD)$, $Y(KD)$, $F(LD,KD)$ |
| LL,KK | Actual sizes: $X(LL)$, $Y(KK)$, $F(LL,KK)$ |
| AX,AY | Logical: $AX = .true.$ denotes interpolation is along an X gridline. $AY = .true.$ denotes interpolation along a Y gridline. |

Theory

The function F is evaluated at the point (XP,YP) using simple divided differences. This routine differs from INTR3D in that interpolation is strictly along a gridline.

Subroutine INTR3D

Object

This subroutine interpolates a function F to a point in between gridlines, using linear interpolation of a first order tensor product approximation of the function F .

Options

None

List of Symbols

| | |
|-------|--|
| X | Ordinates |
| Y | Abscissa |
| F | Function $F(X,Y)$ |
| L,K | Indices of Interpolation |
| XP,YP | Point of Interpolation |
| FP | $F(XP,YP)$ |
| DFDX | $d(F(XP,YP))/dx$ |
| DFDY | $d(F(XP,YP))/dy$ |
| DFDXY | $d^2(F(XP,YP))/dy^2$ |
| LL,KL | Dimensions: $X(LL)$ $Y(KL)$ $F(LL,KL)$ |

Theory

The function F is locally approximated by the first order tensor product:

$$F = (ax+b)*(cy+d) \quad (1)$$

where a, b, c and d are chosen so that the local approximation agrees with the actual function values at the four corners of grid box whose lower lefthand corner has indices (L, K) . The returned function value and derivatives are evaluated directly from F' .

Subroutine LAG4PT

Object

This subroutine interpolates the function and the first and second derivatives using a four point Lagrangian interpolation.

Options

None

List of Symbols

| | |
|-------|--------------------------|
| X(I) | Input abscissas |
| Y(I) | Input ordinates |
| XARG | Output abscissa |
| YARG | Output ordinate |
| DYDX | Output first derivative |
| D2YDX | Output second derivative |

Theory

The four point Lagrangian interpolation formula is:

$$\begin{aligned}
 Y = & \frac{(X - X(I+1))(X - X(I+2))(X - X(I+3))Y(I)}{(X(I) - X(I+1))(X(I) - X(I+2))(X(I) - X(I+3))} \\
 & - \frac{(X - X(I))(X - X(I+2))(X - X(I+3))Y(I+1)}{(X(I) - X(I+1))(X(I+1) - X(I+2))(X(I+1) - X(I+3))} \\
 & + \frac{(X - X(I))(X - X(I+1))(X - X(I+3))Y(I+2)}{(X(I) - X(I+2))(X(I+1) - X(I+2))(X(I+2) - X(I+3))} \\
 & - \frac{(X - X(I))(X - X(I+1))(X - X(I+2))Y(I+3)}{(X(I) - X(I+3))(X(I+1) - X(I+3))(X(I+2) - X(I+3))}
 \end{aligned} \tag{1}$$

The first and second derivatives are obtained by analytically differentiating Eq. (1).

Subroutine METCO

Object

This subroutine calculates the covariant metric tensor components $GLIJ$, the contravariant metric tensor components $GUIJ$, the metric coefficients HHI , and their derivatives.

Options

None

List of Symbols

See COMMON blocks

Theory

Given all the partial derivatives of the transformation calculated in subroutine INTRC, the metric data is then given by:

$$G_{ij} = \frac{dY_K}{dX_i} \frac{dY_K}{dX_j} \quad (1)$$

$$H_1 = \sqrt{G_{11}} \quad (2)$$

$$H_2 = \sqrt{G_{22}} \quad (3)$$

$$H_3 = 1.0 \quad (4)$$

$$G = \det(G_{ij}) \quad (5)$$

$$G^{ij} = (G_{rs}G_{lt} - G_{rt}G_{ls})/G \quad (6)$$

where the groups (i,r,l) and (j,s,t) are cyclic permutations. The derivatives are obtained by differentiating Eq. (1).

Subroutine OPEC(X,F,FPA,FPB,NP1)

Object

This subroutine calculates the one sided proximate end conditions for the surface spline interpolation.

Options

None

List of Symbols

| | |
|-----|---|
| X | Abcissas |
| F | Ordinates |
| FPA | Left hand derivative end condition |
| FPB | Right hand derivative end condition |
| NP1 | Number of ordered pairs of data (NP1>4) |

Theory

This subroutine evaluates the derivative boundary conditions for the cubic spline which is fitted to the input coordinates of the blade surface using the theory of McCartin (Ref 1.). This subroutine is called by subroutine SPLINE.

References

1. McCartin, B. J. : Theory, Computation, and Application of Exponential Splines, Courant Mathematics and Computing Laboratories, October 1981.

Subroutine OPTDAT

Object

This subroutine echo prints the input data.

Options

None

List of Symbols

See COMMON blocks

Theory

This subroutine echo prints the input data, prints the reference conditions calculated in subroutine REFCON, prints the smoothed pressure CP data calculated in subroutine SMTHD, and finally prints the rotor inlet conditions calculated in subroutine RINLET.

Subroutine REFCON

Object

This subroutine calculates the reference conditions to normalize all input variables.

Options

IOPT8 = 0 (Stator) No coriolus forces

IOPT8 = 1 (Rotor) Load pressure data hub to tip

IOPT8 = -1 (Rotor) Load pressure data tip to hub

List of Symbols

See COMMON blocks

Theory

The reference conditions are defined in Ref. 1 as used in the BL3D boundary layer code.

References

1. Anderson, O.L.: Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.

Subroutine RINLET

Object

This subroutine calculates the rotor inlet conditions.

Options

IOPT8 = 0 (Stator) Non coriolus forces
 IOPT8 = 1 (Rotor) Load pressure data hub to tip
 IOPT8 = -1 (Rotor) Load pressure data tip to hub
 IOPT11 = 0 Uniform upstream conditions
 IOPT11 = 1 Nonuniform upstream conditions
 IOPT11 = 2 Approx. upstream cond. for rotor

List of Symbols

| | |
|-------|--|
| DUPDR | Derivative of absolute tangential velocity |
| GAP | Gap normal to flow direction |
| HGT | Span |
| OMEGZ | Axial component of absolute vorticity |
| | Axial component of relative vorticity |
| | Steamwise component of relative vorticity |
| | Average relative vorticity |
| | Steam function |

Theory

The total pressure PTAI(K), total temperature TTAI(K), axial velocity UZAI(K), and rotor inlet relative angle BTRI(K) are known from the input data. Both the relative and absolute velocity components can be calculated from the velocity triangles. Knowing the absolute velocities, the static enthalpy and static pressure can then be calculated.

The relative rotor inlet vorticity and the initial spanwise velocities as estimated using the theory of Dring and Joslyn, Ref. 1. The absolute vorticity is given approximately by

$$\omega_z = \frac{1}{R} \frac{\partial (RU_\phi)}{\partial R} \quad (1)$$

and the relative vorticity by

$$\zeta_z = \omega_z - 2\bar{\Omega} \quad (2)$$

The component of vorticity in the streamwise direction is then

$$\zeta_s = \zeta_z U_z / U_1 \quad (3)$$

An estimate of the initial spanwise velocity on the rotor blade is obtained by solving Poisson's equation using the area average vorticity.

$$\nabla^2 \psi = \zeta_{ZA} \quad (4)$$

A Fourier series solution of Eq. (4) is given by (Ref. 2) as

$$\psi = -\frac{\zeta_{ZA}}{2} x(g-x) + \frac{4\zeta_{ZA}g^2}{\pi^3} \sum_{k=1}^{\infty} \sin\left[\frac{k\pi x}{g}\right] \frac{\cosh\left[\frac{k\pi}{g}(y-h/2)\right]}{k^3 \cosh\left[\frac{k\pi}{g}h/2\right]} \quad (5)$$

where K is odd. The estimated spanwise velocity at the leading edge is given by

$$V(0,Y) = g\zeta_{SA} \left\{ \frac{1}{2} - \frac{4}{\pi^2} \sum_{k=1}^{\infty} \frac{\cosh\left[\frac{k\pi}{g} (Y-h/2)\right]}{k^2 \cosh\left[\frac{k\pi}{g} h/2\right]} \right\} \quad (6)$$

References

1. Dring, R. P. and H. D. Joslyn: The Relative Eddy in Axial Turbine Rotor Passages. ASME Paper 83-GT-22, 1983.
2. Carslaw, H. S. and J. C. Jaeger: Conduction of Heat in Solids. 2nd Edition, Oxford University Press, 1959.

Subroutine ROTOR

Object

This subroutine calculates the upstream total pressure, total enthalpy (rothalpy) and local vorticity component normal to the surface

Options

IOPT8 = 0 (Stator) Non coriolus forces

IOPT8 = 1 (Rotor) Load pressure data hub to tip

IOPT8 = -1 (Rotor) Load pressure data tip to hub

IOPT11 = 0 Uniform upstream conditions

IOPT11 = 1 Nonuniform upstream conditions

IOPT11 = 2 Approx. upstream cond. for rotor

List of Symbols

See COMMON blocks

Theory

The upstream conditions PTABSI,TTABSI,UZABSI,BETARI, are linearly interpolated from the input data. The velocities are then calculated from the velocity triangles and the relative total enthalpy and rothalpy are given by,

$$H_T = \tilde{H}_T - U_\phi^2 - V_B^2/2 \quad (1)$$

$$I = H_T - V_B^2/2 \quad (2)$$

The component of vorticity normal to the surface is then

$$\Omega_3 = \gamma_{13}^{-1} \tilde{\omega}_1 + \gamma_{23}^{-1} \tilde{\omega}_2 + \gamma_{33}^{-1} \tilde{\omega}_3 \quad (3)$$

Subroutine SMTHD

Object

This subroutine smooths the input CP data

Options

IOPT7 = 0 Do not smooth data

IOPT7 > 0 Smooth data IOPT7 times

List of Symbols

See COMMON blocks

Theory

The input data is first interpolated from the input LILAST*KILAST grid to a LDL*KDL grid. Then the CP data is smoothed by averaging with its neighboring points using the formula

$$\bar{f}_K^L = (f_K^{L+1} + f_K^{L-1} + f_{k+1}^L + f_{K-1}^L)/8 + f_k^L/2 \quad (1)$$

Subroutine SOLVE

Object

This subroutine calculates the geometric coordinate data and the boundary layer edge conditions for use by the UTRC boundary layer code.

Options

IOPT6 Print every IOPT6'th station

IOPT9 = 0 Output coordinates Y1 and Y2

IOPT9 = 1 Output arc lengths S1 and S2

List of Symbols

See COMMON blocks

Theory

This subroutine first calculates the computational step size in both the X1 and X2 directions. A double DO LOOP sweeps through the mesh and calls the sub-routines as follows:

INTRB Establish mapping of boundaries

INTRC Establish surface geometry

METCO Calculate metric data

DIRCOS Calculate direction cosines

ROTOR Calculate upstream total enthalpy, total pressure and vorticity component normal to surface

INTRD Interpolate pressure distribution

BLEDGE Calculate b. l. edge conditions

At each L,K mesh point the following data is written on the output files:

| | | |
|-------|----|--------------------------|
| IDRM1 | 8 | metric data |
| IDRM2 | 9 | edge conditions |
| IDRM3 | 10 | transformation variables |
| IDRM4 | 11 | length scales |
| IDRM5 | 12 | setup code output |

Subroutine UITER(Arg. List)

Object

This subroutine solves finite difference equations for the boundary layer edge velocities U1E , U2E using an iteration algorithm based on successive substitution.

Options

None

List of Symbols

| | |
|-----------|-------------------------------------|
| A0 to A14 | Coefficients of edge equations |
| C1 to C6 | Coefficients of edge equations |
| B1 to B12 | Coefficients of algebraic equations |
| L , K | Index for X1 and X2 |

Theory

This subroutine solves a set of quadratic algebraic equations by successive substitution as described in Sec. 3.8 in Ref. 1.

References

1. Anderson, O. L. : Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.

7.0 DESCRIPTION OF BL3D CODE

7.1 BL3D Main Program

The main program for the BL3D code opens and closes all input and output files and calls the subroutines which execute the primary tasks depending on the input options described in Section 5.1. An overall view of the BL3D code is shown on the Global Tree Structure Chart shown on the following pages. This tree structure is arranged by tasks and labeled as they appear in the main program BL3D. Column 1 shows the main program which calls the subroutines in Column 2. Each subroutine in Column 2 executes a major task and calls the subroutine in Column 3. For any given calculation not all branches of the tree are called.

Chart II Global Tree Structure by Task

| | | | | |
|------|---|--|--|--|
| MAIN | | | | |
| 1.0 | Open Input/Output File | | | |
| | PREP | | | |
| 2.0 | Read Input Data | | | |
| | RINPUT | | | |
| 3.0 | Initialize Parameters and Arrays | | | |
| | RINIT | | | |
| 4.0 | Start Outer Do Loop (L=1, IXEND) | | | |
| | 4.01 Read Metric Data, Edge Conditions, and Direction Cosines | | | |
| 5.0 | Start Inner Do Loop (K=1, IWEND) | | | |
| | 5.01 Set Boundary Layer Edge Conditions | | | |
| | EDGE | | | |
| | 5.02 Calculate Molecular Viscosity | | | |
| | MOLVIS | | | |
| | 5.03 Calculate Turbulent Viscosity | | | |
| | TURBL | | | |
| | 5.04 Calculate Coefficients of P.D.E. | | | |
| | AXCOEF | | | |
| 6.0 | Start Iteration Loop to Calculate Turbulent Viscosity | | | |
| | MOLVIS TURBL | | | |
| | 6.01 Calculate Coefficients of Matrix Equations | | | |
| | PDCOEF | | | |

Chart II Global Tree Structure by Task (Cont'd)

| | | | | |
|--|--|--|--|--|
| | 6.02 Set Boundary Conditions on Matrix Equations | | | |
| | BNDCND | | | |
| | 6.03 Invert Matrix Equations | | | |
| | SOLVE | | | |
| | 6.04 Set Solution Arrays on Inflow Plains | | | |
| | SYMSET | | | |
| | 6.05 Check for Convergence | | | |
| | 6.06 Calculate and Write Output Data | | | |
| | ROUTPT | | | |
| | 6.07 Reinitialize Solution for Next Point | | | |
| | NEXTPT | | | |
| | 7.0 End Inner Do Loop | | | |
| | 8.0 End Outer Do Loop | | | |
| | 9.0 Close Input/Output Files | | | |
| | POSTP | | | |

7.2 BL3D COMMON Block Variables

PARAMETERS

| | | |
|-------|-------|---|
| NPHI | (61) | Max. no. X_2 mesh points |
| NXDIM | (101) | Max. no. X_1 mesh points |
| NORM | (201) | Max. no. X_3 mesh points |
| IDRM0 | (7) | Printed output unit |
| IDRM1 | (10) | Coordinate and metric data input unit no. |
| IDRM2 | (11) | Boundary layer edge data input unit no. |
| IDRM3 | (12) | Direction cosines data input unit no. |
| IDRM4 | (13) | Contour and vector plot output unit no. |
| IDRM5 | (15) | Crossection plot output unit no. |

COMMON /AXCFB/ Coefficients of Partial Differential Eqs.

| | | |
|---------|------------------------|---|
| AX(I) | A | Coefficients of partial differential eqs. |
| Q | q | Levy - Lees length scale parameter |
| Q0 | q_0 | Levy - lees length scale parameter at $X_2 = 0$. |
| GBAR(K) | $\bar{\epsilon}_{ref}$ | Reference turbulent/laminar viscosity ratio |

COMMON /CNTRL/ Integer Parameters

| | | |
|-------|--------|--|
| IE | | No. X_3 mesh points for energy eq. |
| IM | (IE-1) | No. X_3 mesh points for momentum eq. |
| IXEND | | No. X_1 mesh points |
| IWEND | | No. X_2 mesh points |

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| | |
|--------|---------------------------------------|
| ITURB | Turbulence model input option |
| IGBAR | Levy - Lees input option |
| IENRGY | Wall boundary condition on energy eq. |
| ITC | Flag for negative temperature |
| IFL | Pointer for direct access files |
| KTC | K counter for BL3D failure |
| KTC1 | KTC - 1 |
| KSP | K counter |
| KSP1 | KSP - 1 |
| KSTOP | Max. no. calculated X_2 mesh points |
| NIT | Iteration counter |
| NITCV | Max. no. iterations |
| CONV | Convergence criteria |
| LSTOP | Max. no. calculated X_1 mesh points |
| LINIT | X_1 inflow option |
| KINIT | X_2 inflow option |

COMMON /EDGEGB/ Boundary Layer edge Conditions

| | | |
|-------|----------|----------------------|
| U(K) | U_{1e} | X_1 edge velocity |
| PP(K) | P_e | Edge static pressure |
| V(K) | U_{2e} | X_2 edge velocity |

| | | |
|------------|----------------------------------|----------------------------|
| DVDW(K) | $\partial U_{2e} / \partial X_2$ | Velocity gradients |
| DUDW(K) | $\partial U_{1e} / \partial X_2$ | |
| DUDX(K) | $\partial U_{1e} / \partial X_1$ | |
| DVDX(K) | $\partial U_{2e} / \partial X_2$ | |
| Y1(K) | Y_1 | Y_1 Cartesian coordinate |
| Y2(K) | Y_2 | Y_2 Cartesian coordinate |
| Y3(K) | Y_3 | Y_3 Cartesian coordinate |
| GAM(I,J,K) | γ_{ij} | Direction cosines |
| HR(K) | I | Rothalpy (enthalpy) |

COMMON /EWINPT/ Input Wall Heat Transfer Variables

| | | |
|-----------|------------------|----------------------|
| EWIN(K,L) | q_w | Wall heat flux array |
| RHWIN | H_w / H_∞ | Wall enthalpy ratio |
| QWSIN | q_w | Wall heat flux |

COMMON /FLORF/ Reference Conditions Parameters

| | | |
|-----|------------|---|
| XMA | M_∞ | Reference freestream Mach no. |
| TFS | t_∞ | Reference freestream static temperature |
| PFS | P_∞ | Reference freestream static pressure |

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| | | |
|--------|-----------------|-----------------------------------|
| UFS | U_{∞} | Reference freestream velocity |
| ROFS | ρ_{∞} | Reference freestream density |
| AMUFS | μ_{∞} | Reference freestream viscosity |
| TREF | t_{ref} | Reference temperature |
| XLREF | l | Reference length scale |
| AMURF | μ_{∞} | Reference viscosity |
| RE | R_e | Reference Reynolds no. |
| REFS | $R_{e\infty}$ | Reference freestream Reynolds no. |
| R | R | Gas constant |
| PR | P_r | Prandtl number (laminar) |
| PRT | P_{rT} | Prandtl number (turbulent) |
| G | γ | Ratio of specific heats |
| CSTAR | C^* | Constant in Sutherlands law |
| RI | | Not used |
| D | | Constant for isentropic flow |
| HO | $H_{T\infty}$ | Reference rothalpy |
| CPRIME | C' | Constant |
| VK | | Constant |
| CP | C_p | Pressure coefficient |

COMMON /METCB/ Coordinate Data

| | | |
|-------|-------|----------------------------|
| H1(K) | H_1 | X metric scale coefficient |
| H2(K) | H_2 | X metric scale coefficient |

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| | | | |
|-----------|----------------------------------|---|---|
| DH1DX(K) | $\partial H_1 / \partial X_1$ | } | Derivatives of metric scale coefficients |
| DH1DW(K) | $\partial H_1 / \partial X_2$ | | |
| DH2DX(K) | $\partial H_2 / \partial X_1$ | | |
| DH2DW(K) | $\partial H_2 / \partial X_2$ | | |
| G12(K) | G_{12} | | Covariant metric component |
| DG12DX(K) | $\partial G_{12} / \partial X_1$ | } | Derivatives of covariant metric component |
| DG12DW(K) | $\partial G_{12} / \partial X_2$ | | |
| GM(K) | $ G $ | | Determinant of metric tensor |

COMMON /PCOEF/ Matrix Elements

| | |
|----------------------|-----------------|
| AU1F,BU1F,CU1F,BU1V, | Matrix elements |
| BU1G,BU1T,BU2F,BU2V, | |
| AU2G,BU2G,CU2G,BU2T, | |
| AEF,BEF,CEF,AEG, | |
| BEG,CEG,AET,BET, | |
| CET,ACF,ACG,BEV, | |
| DU1,DU2,DE,DC | |

COMMON /PPROCB/ Print Control Parameters

| | |
|---------|-----------------------|
| LPRO(L) | L Print control array |
| KPRO(K) | K Print control array |

COMMON /ROTAT/ Rotor Variables

| | | |
|-----------|-----------------------------|---------------------------------------|
| RAD(K) | R | Radius |
| DRADX(K) | $\partial R / \partial X_1$ | Derivatives of Radius |
| DRADW(K) | $\partial R / \partial X_2$ | |
| OMEGA | Ω | Rotor rotational speed |
| OMEGA3(K) | Ω_3 | Vorticity component normal to surface |

COMMON /STPSIZ/ Step Size Variables

| | | |
|---------|--------------------------|---|
| XI1(L) | ξ_1^L | Levy - Lees coordinate in X_1 direction |
| DXI1(L) | $\Delta \xi_1^L$ | Levy - Lees step size in X_1 direction |
| DXV(L) | ΔX_1 | Coordinate step size in X_1 direction |
| X0 | X_{10} | Virtual origin for X_1 direction |
| WV(K) | $X_{2,k}$ | Coordinate in X_2 direction |
| DWV(K) | $\Delta X_{2,k}$ | Coordinate step size in X_2 direction |
| W0 | X_{20} | Virtual origin for X_2 direction |
| XN(N) | ξ_3 | Levy - Lees coordinate in X_3 direction |
| DN(N) | $\Delta \xi_3$ | Levy - Lees step size in X_3 direction |
| DN1 | $(\Delta \xi_3)_{\xi=0}$ | Initial step size in X_3 direction |
| AK | ξ_3 | Stretching parameter |

COMMON /TURBCB/ Turbulent Flow Variables

| | | |
|-------|---------------|--|
| E1(K) | $1 + E_1/\mu$ | Ratio turbulent/laminar viscosity X_1 momentum eq. |
| E2(K) | $1 + E_2/\mu$ | Ratio turbulent/laminar viscosity X_2 momentum eq. |

| | | |
|-------|------------------------|--|
| E3(K) | $1 + P_r/P_{rT} E/\mu$ | Ratio turbulent/laminar viscosity energy eq. |
| EM(K) | E/μ | Ratio eddy/laminar viscosity |
| XT1 | X_{T1} | Start of transition |
| XT2 | X_{T2} | End of transition |
| CISO | C_{S0} | Ratio $E2/E1$ |
| XTRAN | X_T | Transition coordinate length |

COMMON /VELL/ Boundary Layer Edge Parameters

| | | |
|-------|-----------------------------------|--|
| VCAP | U_{1e} | X_1 edge velocity |
| TCAP | T_e | Edge static temperature |
| CVCAP | U_{2e} | X_2 edge velocity |
| PCAP | P_e | Edge static pressure |
| DTCDX | $\partial T_e / \partial X_1$ | Derivatives of edge temperature |
| DTCDW | $\partial T_e / \partial X_2$ | |
| DVCDX | $\partial U_{1e} / \partial X_1$ | Derivatives of X_1 edge velocity |
| DVCDW | $\partial U_{1e} / \partial X_2$ | |
| DCCDX | $\partial U_{2e} / \partial X_1$ | Derivatives of X_1 edge velocity |
| DCCDW | $\partial U_{2e} / \partial X_2$ | |
| DPCDX | $\partial C_p / \partial X_1$ | Derivatives of static pressure |
| DPCDW | $\partial C_p / \partial X_2$ | |
| VR | U_{ref} | Reference edge velocity |
| DVRDX | $\partial U_{ref} / \partial X_1$ | Derivatives of reference edge velocity |
| DVRDW | $\partial U_{ref} / \partial X_2$ | |

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| | | |
|--------|---|--|
| HE | H_{Te} | Edge rothalpy |
| DHEDX | $\partial H_{Te} / \partial X_1$ | Derivatives of edge rothalpy |
| DHEDW | $\partial H_{Te} / \partial X_2$ | |
| ROCAP | ρ_e | Edge density |
| ROMU | L | Edge Levy - Lees parameter |
| AMUE | μ_e / μ_{ref} | Edge viscosity |
| DCCDWX | $\partial^2 U_{2e} / \partial X_1 \partial X_2$ | Limiting derivative at symmetry boundary |

COMMON /VISC/ Dependent Variables

| | | |
|--------|--|------------------------------------|
| VIS(N) | L | Levy - Lees stretching function |
| V2(N) | $V_{,K}^L$ | Normal velocity ratio |
| V3(N) | $V_{,K-1}^L$ | Normal velocity ratio |
| F3N(N) | $(\partial F / \partial \xi_3)_{,K-1}^L$ | Derivative of X_1 velocity ratio |
| G3N(N) | $(\partial G / \partial \xi_3)_{,K-1}^L$ | Derivative of X_2 velocity ratio |
| F2(N) | $F_{,K}^L$ | X_1 velocity ratio |
| G2(N) | $G_{,K}^L$ | X_2 velocity ratio |
| T2(N) | $T_{,K}^L$ | Static temperature ratio |
| F2N(N) | $(\partial F / \partial \xi_3)_{,K}^L$ | Derivative of X_1 velocity ratio |
| G2N(N) | $(\partial G / \partial \xi_3)_{,K}^L$ | Derivative of X_2 velocity ratio |
| F1(N) | $F_{,K}^{L-1}$ | X_1 velocity ratio |
| G1(N) | $G_{,K}^{L-1}$ | X_2 velocity ratio |

| | | |
|---------|--|------------------------------------|
| F1N(N) | $(\partial F / \partial \xi_3)_{,K}^{L-1}$ | Derivative of X_1 velocity ratio |
| G1N(N) | $(\partial G / \partial \xi_3)_{,K}^{L-1}$ | Derivative of X_2 velocity ratio |
| Y(N) | Y_3 | Distance from wall |
| F3(N) | $F_{,K-1}^L$ | X_1 velocity ratio |
| G3(N) | $G_{,K-1}^L$ | X_2 velocity ratio |
| TT1(N) | $H_{,K}^{L-1}$ | Total enthalpy ratio |
| TT2(N) | $H_{,K}^L$ | Total enthalpy ratio |
| TT3(N) | $H_{,K-1}^L$ | Total enthalpy ratio |
| TT1N(N) | $(\partial H / \partial \xi_3)_{,K}^{L-1}$ | Derivative of total enthalpy ratio |
| TT2N(N) | $(\partial H / \partial \xi_3)_{,K}^L$ | Derivative of total enthalpy ratio |
| TT3N(N) | $(\partial H / \partial \xi_3)_{,K-1}^L$ | Derivative of total enthalpy ratio |
| TT4N(N) | $(\partial H / \partial \xi_3)_{,K+1}^{L-1}$ | Derivative of total enthalpy ratio |
| F4(N) | $F_{,K+1}^{L-1}$ | X_1 velocity ratio |
| G4(N) | $G_{,K+1}^{L-1}$ | X_2 velocity ratio |
| V4(N) | $V_{,K+1}^{L-1}$ | Normal velocity ratio |

7.3 Description of BL3D Subroutines

| | |
|--------|---|
| AXCOEF | Calculate coefficients of differential eqs. |
| BNDCND | Set boundary conditions for matrix eqs. |
| EDGE | Set boundary layer edge conditions |
| MAIN | Main program |
| MOLVIS | Calculate Levy-Lees function |
| NEXTPT | Reinitialize solution arrays for next point |
| PDCOEF | Calculate coefficients of matrix equations |
| POSTP | Close input/output files |
| PREP | Open input/output files |
| RINIT | Initialize parameters and arrays |
| RINPUT | Read input data |
| ROUTPT | Calculate and write output data |
| SOLVE | Invert matrix equations |
| SYMSET | Set solution arrays at starting planes |
| TURBL | Calculate turbulent viscosity |

Subroutine BNDEND(Arg. List)

Object

This subroutine sets the boundary conditions on the matrix equations.

Options

KINIT = 0 Local similarity start at $X_2 = 0.0$

KINIT = 1 Plane of symmetry start at $X_2 = 0.0$

IERNGY = 0 Specify wall temperature

IERNGY = 1 Specify wall heat flux

List of Symbols

| | |
|-------|--|
| EIE | Edge value of total enthalpy function |
| EW | Wall value of total enthalpy function |
| EWP | Wall value of enthalpy derivative function |
| FIE | Edge value of X_1 velocity function |
| GIE | Edge value of X_2 velocity function |
| L , K | Index for X_1 and X_2 respectively |

Theory

The boundary conditions are given Sect. 3.6 of Ref. 1. At the edge of the boundary layer the conditions are:

$$F_e = 1.0 \quad (1)$$

$$H_e = 1.0 \quad (2)$$

$$G_e = U_3/U_{ref} \quad (3)$$

At the wall the conditions are

$$G_e = 1.0 \quad \text{if KINIT=1 and K=1} \quad (4)$$

$$H_e = (T_w/T_\infty) H_{T_\infty} / H_{T_e} \quad \text{if IENRGY=0} \quad (5)$$

$$\left(\frac{\partial H}{\partial \xi_e} \right)_w = \frac{-q_w \ell P_r \sqrt{2 \xi_1 / R_e}}{\left(H_{T_\infty} U_\infty^2 \right) \left[\left(\frac{\rho_w \mu_w}{\rho_e \mu_e} \right) (\rho_e \mu_e) \right] h_2 U_{1e} \mu_{ref}} \quad \text{if IENERGY = 1} \quad (6)$$

References

1. Anderson, O. L. : Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.

Subroutine EDGE(Arg. List)

Object

This subroutine sets the boundary layer edge conditions.

Options

LINIT = 0 Local similarity start at $X_1 = 0.0$

LINIT = 1 Flat plate similarity start at $X_1 = 0.0$

LINIT = 2 Stagnation point similarity start at $X_1 = 0.0$

LINIT = 3 Input profiles (not programmed)

KINIT = 0 Local similarity start at $X_2 = 0.0$

KINIT = 1 Plane of symmetry start at $X_2 = 0.0$

KINIT = 2 Input profiles (not programmed)

List of Symbols

See COMMON blocks

Theory

Given U_{1e} , U_{2e} , I_e , and P_e , the remaining edge conditions are given as follows

$$V_B = R\Omega \quad (1)$$

$$H_{Te} = I_e + V_B^2/2 \quad (2)$$

$$U_e^2 = U_{1e}^2 + U_{2e}^2 + 2U_{1e}U_{2e}G_{12}/(H_1H_2) \quad (3)$$

$$T_e = \frac{\gamma-1}{\gamma} [H_{Te} - U_e^2/2] \quad (4)$$

$$P_e = P_e/T_e \quad (5)$$

where the derivatives of the edge conditions are obtained by differentiating Eqs. 1 through 5. The reference conditions are set as follows:

$$U_{\text{ref}} = U_{1e} \qquad K_{\text{INIT}} \neq 1 \qquad (6)$$

$$U_{\text{ref}} = U_{2e} \qquad K_{\text{INIT}} = 1, K = 1 \qquad (7)$$

The edge viscosity is obtained from Sutherland's law.

$$\mu_e = T_e^{3/2} \frac{1 + C'}{T_e + C'} \qquad (8)$$

Subroutine MOLVIS(L,X)

Object

This subroutine calculates the Levy-Lees variable and the static temperature.

Options

None

List of Variables

| | | |
|-------|---------|------------------|
| UTESQ | U_e^2 | Velocity squared |
| X | | Not used |

Theory

The total velocity is given by:

$$U_e^2 = (U_{leF})^2 + (U_{refG})^2 + 2(U_{leF})(U_{refG}) G_{12}/(H_1 H_2) \quad (1)$$

Then the static temperature is given by

$$\Xi = \frac{\gamma-1}{\gamma} \frac{1}{T_e} [H_{Te} H - U_e^2/2] \quad (2)$$

and the Levy-Lees function is calculated from Sutherland's viscosity law where the static pressure is constant in the boundary layer

$$L = \frac{\rho u}{\rho_e u_e} = \Xi^{1/2} \frac{1 + \tilde{C}}{\Xi + \tilde{C}}$$

A check is made on the static temperature during the iteration.

If $\Xi > 0.0$ then ITC = 0

If $\Xi < 0.0$ then ITC = 1

Subroutine NEXTPT(K,L,IFLAG)

Object

This subroutine reinitializes the solution arrays for the next point.

Options

IFLAG = 0 The solution has converged

IFLAG = 1 The solution has not converged

KINIT = 1 Plane of symmetry start on X2 = 0.0

List of Symbols

| | |
|------|-----------------------------------|
| KSP | K |
| KTC | K counter for convergence failure |
| KTC1 | KTC - 1 |
| KSP1 | KSP - 1 |
| IFL | Record counter |

Theory

This subroutine writes the current solution on Unit 8 and reads the appropriate record from Unit 8 to set up the solution arrays at the next point. The record counter IFL is reset to IFL=1 each time L is indexed. Let us define the following vector arrays each representing one record.

$$\left. \begin{aligned}
 f(L,K-1)_1 &= (H(N), F(N), G(N), V(N))_{K-1}^L & N=1, IE \\
 f(L,K)_2 &= (H(N), F(N), G(N), V(N))_K^L & N=1, IE \\
 f(L-1,K)_3 &= (H(N), F(N), G(N), V(N))_K^{L-1} & N=1, IE \\
 f(L-1,K+1)_4 &= (H(N), F(N), G(N), V(N))_{K+1}^{L-1} & N=1, IE
 \end{aligned} \right\} \quad (1)$$

The Unit contains the following records (see Fig. 1):

$$\left. \begin{aligned}
 \text{for } IFL = 1, K & \quad f(L, K) \\
 \text{for } IFL = K+1, KSP & \quad f(L-1, K)
 \end{aligned} \right\} \quad (2)$$

where $KSP < IWEND$. Hence to update the arrays we have:

$$\left. \begin{array}{l} f_1 = f_2 = f(IFL) \\ f_3 = f(IFL+1) \\ f_4 = f(IFL+2) \end{array} \right\} \quad 1 < K < KSP \quad (3)$$

$$\left. \begin{array}{l} f_1 \text{ not needed} \\ f_3 = f(1) \\ f_4 = f(2) \end{array} \right\} \quad K = 1 \quad (4)$$

After the new arrays are set, the normal derivative of the dependent variables are calculated numerically.

Subroutine PDCOEF(L,K,PR)

Object

This subroutine calculates the coefficients of the matrix equations.

Options

None

List of Symbols

| | |
|---|---------------------------|
| AU1F,BU1F,CU1F, BU1V,BU1G,BU1T, DU1 | Coeff. of X1 momentum eq. |
|---|---------------------------|

| | |
|---|---------------------------|
| BU2F,BU2V,AU2G, BU2G,CU2G,BU2T, DU2 | Coeff. of X2 momentum eq. |
|---|---------------------------|

| | |
|---|----------------------|
| AEF,BEF,CEF, BEV,AEG,BEG, CEG,AET,BET CET,DE | Coeff. of energy eq. |
|---|----------------------|

| | |
|------------|--------------------------|
| ACF,ACG,DC | Coeff. of continuity eq. |
|------------|--------------------------|

Theory

In this subroutine the equations of motion are quasi-linearized and discretized to form a set of matrix equations as outlined in Section 3.9 of Ref. 1.

References

1. Anderson, O. L. : Assessmnt of a 3-D Boundary Layer Code to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report UTRC85-4.

Subroutine POSTP

Object

This subroutine closes all input/output files.

Options

None

List of Symbols

See COMMON blocks

Theory

See Sect. 5.3 for a description of all input/output files for the three dimensional boundary layer code.

Subroutine PREP

Object

This subroutine opens all input/output files.

Options

None

List of Symbols

See COMMON blocks

Theory

See Sect. 5.3 for a description of all input/output files for the three dimensional boundary layer code.

$$t_{\text{ref}} = U_{\infty}^2 / R \quad (3)$$

From Sutherland's law we have

$$\mu_{\text{ref}} = 2.27 \times 10^{-8} t_{\text{ref}} / (t_{\text{ref}} + C^*) \quad (4)$$

$$\mu_{\infty} = 2.27 \times 10^{-8} t_{\infty} / (t_{\infty} + C^*) \quad (5)$$

The reference total temperature and total enthalpy are

$$t_{t\infty} = t_{\infty} \left[1 + \frac{\gamma-1}{2} M_{\infty}^2 \right] \quad (6)$$

$$H_{T\infty} = \frac{\gamma}{\gamma-1} \frac{t_{t\infty}}{t_{\text{ref}}} \quad (7)$$

and the reference Reynolds numbers are given by

$$R_e = U_{\infty} \rho_{\infty} l / \mu_{\text{ref}} \quad (8)$$

$$R_{e\infty} = U_{\infty} \rho_{\infty} l / \mu_{\infty} \quad (9)$$

Subroutine RINPUT

Object

This subroutine reads input parameters and flow conditions.

Options

None

List of Symbols

See COMMON blocks

Theory

See Sect. 5.1 for input variables used.

Subroutine ROUTPT

Object

This subroutine calculates output data in an intrinsic coordinate system aligned to the freestream flow direction.

Options

IERNGY = 0 Specify wall temperature

IERNGY = 1 Specify wall heat flux

List of Symbols

| | | |
|---------|------------|---|
| US(N) | U_s | Velocity component tangent to freestream |
| UC(N) | U_c | Velocity component normal to freestream |
| UN(N) | U_n | Not used |
| UT(N) | U_T | Total (magnitude) velocity |
| ALPC(N) | α_c | Angle between \vec{U} and \vec{U}_e |
| ES(N) | e_s | Rate of strain tangent to freestream |
| EC(N) | e_c | Rate of strain normal to freestream |
| EN(N) | e_T | Total (magnitude) rate of strain |
| TS(N) | τ_s | Rate of stress tangent to freestream |
| TC(N) | τ_c | Rate of stress normal to freestream |
| ALP(N) | α | Angle between \vec{U} and \vec{n}_1 |
| THE | θ | Angle between \vec{n}_1 and \vec{n}_2 |
| UT1E | U_{T1e} | Edge velocity tangent to \vec{n}_1 |
| UN1E | U_{N1e} | Edge velocity normal to \vec{n}_1 and \vec{n}_3 |

| | | |
|-------|---------------|--|
| ALPE | α_e | Angle between \vec{U}_e and \vec{n}_1 |
| UTE | U_{Te} | Total edge velocity |
| UT1 | U_{T1} | Velocity tangent to \vec{n}_1 |
| UN1 | U_{N1} | Velocity normal to \vec{n}_1 and \vec{n}_3 |
| E13 | e_{13} | X1 component of $(\vec{E} \circ \vec{n}_3)$ rate of strain |
| E23 | e_{23} | X2 component of $(\vec{E} \circ \vec{n}_3)$ rate of strain |
| ET1 | e_{T1} | Rate of strain $(\vec{E} \circ \vec{n}_3)$ tangent to \vec{n}_1 |
| EN1 | e_{N1} | Rate of strain $(\vec{E} \circ \vec{n}_3)$ normal to \vec{n}_1 and \vec{n}_3 |
| ET | e_T | Magnitude of rate of strain $(\vec{E} \circ \vec{n}_3)$ |
| ALPEE | α_{ee} | Angle between $(\vec{E} \circ \vec{n}_3)$ and \vec{n}_1 |
| ALPEC | α_{ec} | Angle between $(\vec{E} \circ \vec{n}_3)$ and \vec{U}_e |
| T13 | τ_{13} | X1 component of $(\vec{T} \circ \vec{n}_3)$ rate of stress |
| T23 | τ_{23} | X2 component of $(\vec{T} \circ \vec{n}_3)$ rate of stress |
| TAUT1 | τ_{T1} | Rate of stress $(\vec{T} \circ \vec{n}_3)$ tangent to \vec{n}_1 |
| TAUN1 | τ_{N1} | Rate of stress $(\vec{T} \circ \vec{n}_3)$ normal to \vec{n}_1 and \vec{n}_3 |
| TAU | τ | Magnitude of rate of stress |
| ALPT | α_T | Angle between $(\vec{T} \circ \vec{n}_3)$ and \vec{n}_1 |
| ALPC | α_c | Angle between $(\vec{T} \circ \vec{n}_3)$ and \vec{U}_e |
| DY3 | ΔY_3 | Difference - normal coordinate |

| | | |
|--------|----------------------|--------------------------------------|
| DELS | δ_s^*/ℓ | Streamwise displacement thickness |
| DELC | δ_c^*/ℓ | Crossflow displacement thickness |
| DELUS | δ_{us}^*/ℓ | Streamwise velocity thickness |
| DELUC | δ_{uc}^*/ℓ | Crossflow velocity thickness |
| THETSS | θ_{ss}/ℓ | Streamwise momentum thickness |
| THETCC | θ_{cc}/ℓ | Crossflow momentum thickness |
| THETSC | θ_{sc}/ℓ | $U_c \Delta U_s$ momentum thickness |
| THETCS | θ_w/ℓ | $U_s \Delta U_c$ momentum thickness |
| THETHS | θ_{HS}/ℓ | Streamwise enthalpy thickness |
| THETHC | θ_{HC}/ℓ | Crosswise enthalpy thickness |
| THETDS | θ_{DS}/ℓ | Streamwise dissipation thickness |
| THETDC | θ_{DC}/ℓ | Crosswise dissipation thickness |
| HSS | H_{SS} | Shape factor |
| YEDGE | δ | Edge of boundary layer |
| CFS | C_{fs} | Streamwise wall friction coefficient |
| CFC | C_{fc} | Crossflow wall friction coefficient |
| QW | Q_w | Wall heat flux |
| ST | S_t | Stanton number |
| TWAD | T_a | Adiabatic wall temperature |
| TW | T_w | Wall temperature |
| RECFAC | R_{ec} | Recovery factor |

| | | |
|-----------|--------------------|--|
| V1E,V2E | V_1, V_2 | Cartesian components of edge velocity |
| BETAE | β_e | Flow angle at the edge relative to Y_1 |
| BETAW | β_w | Flow angle at the wall relative to Y_2 |
| EPS1W | ϵ_{1w} | Y_1 component of wall rate of strain |
| EPS2W | ϵ_{2w} | Y_2 component of wall rate of strain |
| E131 | ϵ_{13w} | E13 at the wall |
| E231 | ϵ_{23w} | E23 at the wall |
| BET1,BET2 | β_1, β_2 | Characteristic directions |

Theory

Consider a vector \vec{A} in a nonorthogonal coordinate system (X_1, X_2, X_3) with the corresponding unit vectors $(\vec{n}_1, \vec{n}_2, \vec{n}_3)$. Then, neglecting the normal component, we have for the contravariant components:

$$\vec{A} = A^1 \vec{n}_1 + A^2 \vec{n}_2 + 0 \vec{n}_3 \quad (1)$$

The angle between A^1 and A^2 is given by

$$\cos \theta = G_{12} / (H_1 H_2) \quad (2)$$

Let us now resolve the vector in components tangent to \vec{n}_1 and normal to \vec{n}_1 .

$$\vec{A} = A_T \vec{n}_1 + A_N (\vec{n}_1 \times \vec{n}_3) + 0 n \quad (3)$$

Clearly as shown in Fig. 1 we have:

$$A_T = A^1 + A^2 \cos \theta \quad (4)$$

$$A_N = (A^2 + \sin \theta) \quad (5)$$

$$|\vec{A}| = (A_T^2 + A_N^2)^{1/2} \quad (6)$$

$$\alpha = \tan (A_N/A_T) \quad (7)$$

Let us now define an intrinsic coordinate system referenced to the freestream direction. Then applying the above formulas for ($A = U$) we have:

$$U_{T1e} = U_{1e} + U_{2e} \cos \theta \quad (8)$$

$$U_{N1e} = U_{2e} \sin \theta \quad (9)$$

$$U_e = (U_T^2 + U_N^2)^{1/2} \quad (10)$$

$$\alpha_e = \tan(U_{N1e}/U_{T1e}) \quad (11)$$

Then for any velocity in the boundary layer we have:

$$U_{T1} = U_1 + U_2 \cos \theta \quad (12)$$

$$U_{N1} = U_2 \sin \theta \quad (13)$$

$$U_T = (U_T^2 + U_N^2)^{1/2} \quad (14)$$

$$\alpha = \tan(U_{N1}/U_{T1}) \quad (15)$$

Hence the angle between the local flow direction and the free stream flow direction is:

$$\alpha_c = \alpha - \alpha_e \quad (16)$$

and the velocity components tangent and normal to the freestream direction are:

$$U_s = U_T \cos \alpha_c \quad (17)$$

$$U_c = U_T \sin \alpha_c \quad (18)$$

For the rate of strain components and rate of stress components we form the vectors

$$\dot{A} = \dot{\bar{E}} \circ \vec{n}_3 = e_{13} \vec{n}_1 + e_{23} \vec{n}_2 \quad (19)$$

$$\dot{A} = \dot{\bar{T}} \circ \vec{n}_3 = \tau_{13} \vec{n}_1 + \tau_{23} \vec{n}_2 \quad (20)$$

where the components are given by

$$C_o = \sqrt{R_e} \rho_e U_{1e} H_2 / \sqrt{2\xi_1} \quad (21)$$

$$C_1 = C_o / R_e \mu_o / \mu_{ref} \epsilon_{ref} \ell \quad (22)$$

$$e_{13} = C_o U_{1e} \rho / \rho_e \partial F / \partial \xi_3 \quad (23)$$

$$e_{23} = C_o U_{ref} \rho / \rho_e \partial G / \partial \xi_3 \quad (24)$$

$$\tau_{13} = C_1 U_{1e} \bar{\epsilon}_1 / \epsilon_{ref} \partial F / \partial \xi_3 \quad (25)$$

$$\tau_{23} = C_1 U_{ref} \bar{\epsilon}_1 / \epsilon_{ref} \partial G / \partial \xi_3 \quad (26)$$

and apply the same formula. With the flow angles determined, the characteristic directions are given by:

$$\beta_1 = \text{MAX}(\alpha_c) \quad (27)$$

$$\beta_2 = \text{MIN}(\alpha_c) \quad (28)$$

The boundary layer integral parameters are defined relative to the intrinsic coordinates and are given by:

$$dY_3 = 1/C_o \rho/\rho_e d\xi_e \quad (29)$$

$$\delta_s^*/l = \int \left[1 - \frac{\rho U_s}{\rho_e U_e} \right] dY_3 \quad (30)$$

$$\delta_c^*/l = -\int \left[\frac{\rho U_c}{\rho_e U_e} \right] dY_3 \quad (31)$$

$$\delta_{US}^*/l = \int \left[1 - \frac{U_s}{U_e} \right] dY_3 \quad (32)$$

$$\delta_{UC}^*/l = -\int \left[1 - \frac{U_c}{U_e} \right] dY_3 \quad (33)$$

$$\theta_{ss}/l = \int \frac{\rho U_s}{\rho_e U_e} \left[1 - \frac{U_s}{U_e} \right] dY_3 \quad (34)$$

$$\theta_{cc}/l = -\int \frac{\rho U_s}{\rho U_c} \frac{U_c}{U_e} dY_3 \quad (35)$$

$$\theta_{sc}/l = \int \frac{\rho U_c}{\rho_e U_e} \left[1 - \frac{U_s}{U_e} \right] dY_3 \quad (36)$$

$$\theta_{cs}/l = \int \frac{\rho U_s}{\rho_e U_e} \frac{U_c}{U_e} dY_3 \quad (37)$$

$$\theta_{HS}/l = \int \frac{\rho U_s}{\rho_e U_e} \left[1 - \left(\frac{U_s}{U_e} \right)^2 \right] dY_3 \quad (38)$$

$$\theta_{HC}/l = \int \frac{\rho U_c}{\rho U_e} \left(\frac{U_c}{U_e} \right)^2 dY_3 \quad (39)$$

$$\theta_{DS}/l = \int \frac{\tau_s}{\rho_e U_e^2} \frac{e_s}{U_e} dY_3 \quad (40)$$

$$\theta_{DC}/l = \int \frac{\tau_c}{\rho_e U_e^2} \frac{e_c}{U_e} dY_3 \quad (41)$$

The wall friction coefficients are given by

$$C_{fs} = 2 \tau_{sw}/(\rho_e U_e^2) \quad (42)$$

$$C_{fc} = 2 \tau_{cw}/(\rho_e U_e^2) \quad (43)$$

and the Stanton number by

$$S_t = Q_w / (T_a - T_w) \quad (44)$$

where

$$Q_w = \frac{\gamma-1}{\gamma} \frac{C_o}{R_e P_r} \left(\frac{\rho_w \mu_w}{\rho_e \mu_e} \right) H_{Te} \frac{\mu_e}{\mu_{ref}} \left(\frac{\partial H}{\partial \xi_3} \right)_w \quad (45)$$

The projection of the velocity vector on the Y3 plane are:

$$V_{1e} = \gamma_{11} U_{1e} + \gamma_{21} U_{2e} \quad (46)$$

$$V_{2e} = \gamma_{12} U_{1e} + \gamma_{22} U_{2e} \quad (47)$$

The limiting wall streamline is defined by

$$\lim_{Y_3 \rightarrow 0} \frac{V_{2e}}{V_{1e}} = \frac{\epsilon_{2w}}{\epsilon_{1w}} \quad (48)$$

hence

$$\epsilon_{1w} = \gamma_{11} \epsilon_{13w} + \gamma_{21} \epsilon_{23w} \quad (49)$$

$$\epsilon_{2w} = \gamma_{12} \epsilon_{13w} + \gamma_{22} \epsilon_{23w} \quad (50)$$

$$\beta_w = \tan^{-1} (\epsilon_{2w} / \epsilon_{1w}) \quad (51)$$

Subroutine SOLVE(Arg. list)

Object

Solve a set of three second order and one first order partial differential equations forming a block tri-diagonal matrix.

Options

IERNGY = 0 Specify wall temperature

IERNGY = 1 Specify wall heat flux

List of Symbols

| | |
|--|--|
| EIE | Edge value of total enthalpy function |
| EW | Wall value of total enthalpy function |
| EW P | Wall value of enthalpy derivative function |
| FIE | Edge value of X1 velocity function |
| GIE | Edge value of X2 velocity function |
| AU1F,BU1F,CU1F, BU1V,BU1G,BU1T, DU1 | Coeff. of X1 momentum eq. |
| BU2F,BU2V,AU2G, BU2G,CU2G,BU2T, DU2 | Coeff. of X2 momentum eq. |
| AEF,BEF,CEF, BEV,AEG,BEG, CEG,AET,BET, CET,DE | Coeff. of energy eq. |
| ACF,ACG,DC | Coeff. of continuity eq. |
| PF,QF,RF,SF,TF, PG,QG,RG,SG,TG, PE,QE,RE,SE,TE | Coeff. of upper triangular matrix |

Theory

The block tri-diagonal matrix is reduced to the upper triangular matrix using block factorization in which the continuity equation is eliminated from the matrix reduction by direct substitution. The center block is inverted using Cramer's rule. The reduction process starts at the outer edge ($N = IE$) where the boundary conditions are known explicitly and continue to ($N=1$) where the derivative boundary condition is evaluated. In the backward substitution the coefficients for the normal velocity are evaluated from the other coefficients.

Subroutine TURBL(K,L,X,ICNTRL)

Object

This subroutine calculates the turbulent viscosity and the turbulent Levy-Lees parameter.

Options

ICNTRL = 0 Not used at the present time

= 1

ITURB = 0 Laminar flow

= 1 Turbulent/transitional flow

IGBAR = 0 Laminar Levy-Lees variables

= 1 Turbulent Levy-Lees variables

List of Symbols

| | | |
|-------|------------------|----------------------------|
| BET | X_3 | X3 Distance normal to wall |
| EMO | ϵ_o/μ | Eddy viscosity outer layer |
| L , K | | Mesh point indices |
| X | X_1 | X1 coordinate distance |
| XTRAN | X_T | Intermittancy factor |

Theory

A detailed description of the turbulence model is given in Sect. 3.7 of Ref.

1. The basic turbulence model is that developed by Cebeci and Smith Ref. 2. Then in Levy-Lees variables we have the distance normal to the wall is given by

$$X_3 = \int_0^{\xi} \Xi \, d\xi_3 \quad (1)$$

The outer layer eddy viscosity is then given by

$$\frac{\epsilon_o}{\mu} = X \frac{\sqrt{R_c} [\sqrt{2\xi_1}/H_1]}{[\Xi L (\mu_e/\mu_{ref})]} X_3 (\xi) \quad (2)$$

where the terms in the brackets are coded as local variables. For the inner layer, the eddy viscosity is

$$\frac{\epsilon_i}{\mu} = L^2 \left| \frac{dU}{d\xi_3} \right| \quad (3)$$

where the mixing length is given by

$$L^2 = \left[\frac{K^2 \sqrt{R_e} (\sqrt{2\xi_1}/H_1) X_3^2}{\Xi^2 (\Xi L \mu_e/\mu_{ref})} \right] D^2 \quad (4)$$

and the damping factor by

$$D = 1 - \exp \left\{ \left[\frac{-X_3}{26 (\Xi L \mu_e/\mu_{ref})} \right] \left[\sqrt{\left(\frac{\sqrt{2\xi_1}}{H_1} \right)} \left(\frac{L_w \Xi_w \mu_e \sqrt{R_e}}{\Xi^2 \mu_{ref}} \right) \left| \frac{dU}{d\xi_3} \right| \right] \right\} \quad (5)$$

The Clauser outer layer constant is usually taken to be

$$\chi = 0.0168 \quad (6)$$

and the Prandtl constant by

$$K = 0.4357 \quad (7)$$

The eddy viscosity is then given by

$$\begin{aligned} \frac{\epsilon}{\mu} &= \frac{\epsilon_i}{\mu} X_T \text{ if } \frac{\epsilon_i}{\mu} < \frac{\epsilon_o}{\mu} \\ &= \frac{\epsilon_o}{\mu} X_T \text{ if } \frac{\epsilon_i}{\mu} > \frac{\epsilon_o}{\mu} \end{aligned} \quad (8)$$

where X_T is the intermittency factor derived from Dhawan and Narasimha, Ref.

3.

$$X_T = \{ 1 - \exp [-4.6513 \left(\frac{X - X_{ri}}{X_{T2} - X_{T1}} \right)^2] \} \quad (9)$$

The turbulent Levy-Lees parameter is then determined by the eddy viscosity in the outer layer

$$\begin{aligned} \bar{\epsilon}_{ref} &= 1 & \text{IGBAR} &= 0 \\ &= 1 + \frac{\epsilon_o}{\mu} X_T & \text{IGBAR} &= 1 \end{aligned} \quad (10)$$

References

1. Anderson, O. L. : Assessment of a 3-D Boundary Layer Analysis to Predict Heat Transfer and Flow Field in a Turbine Passage. UTRC Report R85-956834.
2. Cebeci, T. and A. M. O. Smith: Analysis of Turbulent Boundary Layers, Academic Press, New York , 1974.
3. Dhawan, S. and R. Narasimha: Some Properties of Boundary Layer Flow During Transition from Laminar to Turbulent Motion, J. Fluid Mechanics, Vol. 3, 1958.

LIST OF SYMBOLS

| | | |
|------------------|--|------------------------|
| a_n, c_n | Coefficients of boundary edge equations | |
| A_n, K_n | Coefficients of boundary layer equations | |
| c_p, c_v | Specific heats | |
| C_f | Wall friction coefficient | |
| C_p | Pressure coefficient | |
| \vec{e}_i | Unit vectors Cartesian coordinates | |
| F | X_1 velocity ratio | (u_1/u_{1e}) |
| g_{ij}, G_{ij} | Covariant metric tensor components | (g_{ij}/l^2) |
| G | X_2 velocity ratio | (u_2/u_{ref}) |
| h_i, H_i | Metric scale coefficients | (h_i/l) |
| h, H | Static enthalpy | (h/u_∞^2) |
| h_T, H_T | Total enthalpy | (h_T/u_∞^2) |
| H | Total enthalpy ratio | (h_T/h_{Te}) |
| i, I | Rothalpy | (i/u_∞^2) |
| k | Thermal conductivity | |
| l | Reference length | |
| L | Levy - Lees parameter | $(\rho\mu/\rho_e u_e)$ |

| | | |
|--------------------|---|--------------------------------------|
| M | Mach number | |
| \vec{h}_i | Unit vectors surface coordinates | |
| P_T, P_T | Static pressure | $(p/\rho_\infty u_\infty^2)$ |
| p, P | Total pressure | $(P_T/\rho_\infty u_\infty^2)$ |
| P_r, P_{rT} | Prandtl number laminar/turbulent | $(c_p \mu/k)$ |
| q | Levy - Lees length scale parameter | |
| r, R | Radius | (r/l) |
| Re | Reynolds number | $(\rho_\infty u_\infty l/\mu_{ref})$ |
| | Gas constant | |
| s_i, S_i | Arc length distance | (s_i/l) |
| S_t | Stanton number | |
| t, T | Static temperature | (t/t_{ref}) |
| u_i, U_i | Velocity components surface coor. | (u_i/u_∞) |
| u_z, U_z | Axial velocity | (u_z/u_∞) |
| u_r, U_r | Radial velocity | (u_r/u_∞) |
| u_ϕ, U_ϕ | Tangential velocity | (u_ϕ/u_∞) |
| u_{ref}, U_{ref} | X_2 reference velocity u_{1e} or u_{2e} | (u_{ref}/u_∞) |
| v_i, V_i | Velocity components Cartesian coor. | (v_i/u_∞) |
| V | X_3 reduced velocity | |
| v_B, V_B | Rotor velocity | (v_B/u_B) |

| | | |
|------------------------|-------------------------------------|-----------------------|
| x_i, X_i | Surface coordinates | (x_i/l) |
| y_i, Y_i | Cartesian coordinates | (y_i/l) |
| β_1 | Relative inlet flow angle | |
| γ | Ratio of specific heats | |
| γ_{ij} | Direction cosine tensor components | |
| γ_{ij}^{-1} | Inverse tensor components | |
| δ^* | Displacement thickness | |
| ϵ | Eddy viscosity | |
| $\bar{\epsilon}$ | Viscosity ratio turbulent/laminar | |
| $\bar{\epsilon}_{ref}$ | Reference viscosity ratio | |
| θ | Momentum thickness | |
| Ξ | Static temperature ratio | (t/t_{ref}) |
| μ | Molecular viscosity | |
| μ_{ref} | Reference molecular viscosity | $\mu(t_{ref})$ |
| ξ_i | Levy - Lees transformed coordinates | |
| ρ, ϱ | Density | (ρ/ρ_∞) |
| τ_{ij} | Stress components | |
| ω, Ω | Rotor speed | $(\omega l/u_\infty)$ |

Subscripts

| | |
|----------|------------------------------------|
| e | Edge conditions |
| h | Hub |
| L | rotor inlet conditions |
| t | Tip |
| T | Total or stagnation conditions |
| ∞ | Freestream or reference conditions |

Superscripts

| | |
|---|--------------------------------|
| ~ | Absolute rotor reference frame |
|---|--------------------------------|

Tensor Notation

| | |
|-------|--|
| i,j,k | Subscripts covariant tensor components |
| i,j,k | Superscripts contravariant tensor components |

9.0 REFERENCES

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